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Texas Agricultural Extension Service

Agricultural Use of Municipal and Industrial Sludges in the Southern United States

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Agricultural Use of Municipal and Industrial Sludges in the Southern United States

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Chapter 1

Introduction to the Agricultural Use of Municipal and Industrial Sludges

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Nature has always used the land for waste treatment, but more recently man has buried waste in landfills, incinerated it or dumped it in the ocean. Increasing awareness of environmental hazards and degradation of environmental quality during the 1960s led to considerable research on the land treatment of wastes and to the appropriation of federal funds for construction or improvement of municipal treatment plants. Of course, as more waste water was treated and treatment became more efficient, the amount of sludge to be dealt with increased. From 1970 to 1985, municipal sludge production in the U.S. was estimated to double (Walsh, 1976). The estimated municipal sludge production from southern states is shown in Table 1.1.

TABLE 1.1

Estimated production of municipal sludge in the southern states in 1980 and cropland area required for agricultural sludge use.

State	Population[a]	Population on public sewer[a]	Annual sludge production[b]	Land area required if applied at a rate to supply 170 kg available N/ha[c]	
		%	*metric tons/year*	*ha*	*% total cropland*
AL	3,894,000	54	55,000	4,660	0.33
AR	2,286,000	57	35,000	2,960	0.60
FL	4,379,000	73	85,000	7,200	1.31
GA	5,463,000	59	86,000	7,280	0.37
KY	3,661,000	54	52,000	4,400	0.24
LA	4,206,000	72	80,000	6,780	0.47
MS	2,521,000	58	38,000	3,220	0.14
NC	5,882,000	48	75,000	6,350	0.32
OK	3,025,000	73	59,000	5,000	0.12
SC	3,122,000	54	45,000	3,810	0.35
TN	4,591,000	56	68,000	5,760	0.31
TX	14,229,000	82	309,000	26,200	0.29
VA	5,347,000	65	92,000	7,790	0.68

[a]Data from 1980 US Census.
[b]Sludge production estimated at 73 g dry sludge/capita/day.
[c]Assumptions:
(1) Anaerobically digested liquid sludge with 4.4% solids, 290 mg N/L in liquid fraction and 2.6% N in solid fraction (see Table 2-1).
(2) No loss of NH_4-N due to volatilization (e.g. sludge injected) and 30% N in solids becomes available to plants.

Farmers have known the value of organic wastes for crop fertilization for several thousands of years, but during the 1960s and early 1970s, commercial fertilizer was so inexpensive that farmers found it more economical to purchase fertilizer and dispose of manure. When fertilizer prices rose during the mid-1970s (Figure 1.1), there was renewed agricultural interest in the use of municipal and industrial sludges as sources of nutrients for crop production.

Application of sludges is beneficial to agricultural soils in several ways. The greatest benefit is the nitrogen (N) and phosphorus (P) provided for crop nutrition. Sludge

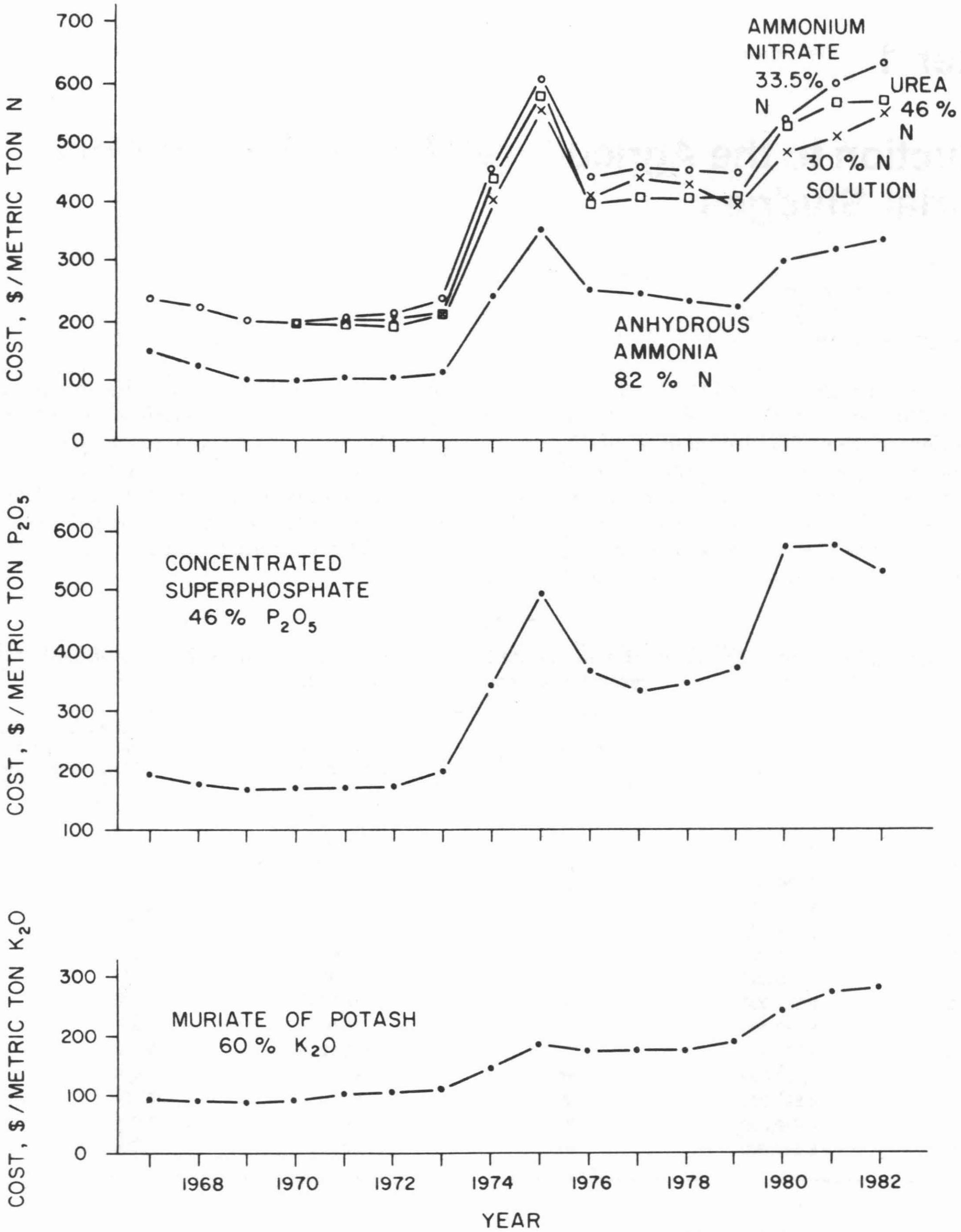

Figure 1.1 Cost of N, P_2O_5 and K_2 fertilizers in the United States, 1967-1982 (USDA, 1973, 1978, 1983).

also supplies organic matter, which improves the physical properties of soil, and micronutrients, which may or may not be needed.

If the sludge produced in each of the southern states were applied at a rate to supply 170 kg/ha of plant available N, the land area required would range from 0.12% of the cropland in Mississippi to 1.31% of the cropland in Florida. Although the total land area likely to receive sludge application is quite small, within economical hauling distances of treatment plants, sludge could have an impact.

Nutrient Content and Availability

The nutrient content of sludges is much lower than that of commercial fertilizers. However, N and P are found at adequate levels in most sludges analyzed, calcium (Ca) is usually adequate, but levels of potassium (K) and magnesium (Mg) are low. Because composition varies greatly, each sludge intended for use on agricultural land should be analyzed separately. Concentrations of all nutrients in sludges from southern states (Table 1.2) are lower than those found in sludges from the Midwest.

Availability of nutrients is more important than total composition because loading rates must be based on available nutrient content. Estimation of availability of sludge N by incubating sludge with soil has shown availabilities of up to 39% of the applied N. Type of sludge, method of pretreatment, and soil type all influence availability.

TABLE 1.2

Median concentrations of N, P and K in sludges from the South.[a]

	N	P	K
	% dry weight		
Municipal sludge	2.6	1.6	0.2
Textile sludge	2.8	0.9	0.2
Fermentation sludge	3.5	0.2	0.1
Wood processing waste	0.4	0.1	0.1

[a]See Appendix Tables 1 and 2 for additional information.

Crop Response

The large range in variability in nutrient availability and crop response under field conditions make it difficult to recommend sludge application rates. The best approach is to make the initial sludge application at a rate based on the best available data for the particular sludge and on soil test and fertilizer recommendations for the site. Plant tissue should be sampled and analyzed during the growing season, and the results used to determine if nutrient concentrations are deficient, sufficient, or excessive. At the end of the growing season, soil samples should be taken to determine if excessive concentrations of inorganic N are present and thus pose a groundwater pollution hazard. These samples can also be used for standard soil testing to determine the status of other plant nutrients in the soils. Adjustments can then be made in sludge or supplemental fertilizer rates the following year.

Heavy Metals

The first consideration should be to ensure that wastes do not contain toxic materials which would preclude future use of the land for crop production or some other useful purpose. Toxicities to crops usually result from applying excessive amounts of copper (Cu), zinc (Zn), and nickel (Ni), but application of excessive amounts of cadmium (Cd) can pose a hazard to animals and humans. Availability of lead (Pb) and chromium (Cr) in soil is very low, but these metals may pose a threat to grazing animals if directly ingested in sludge-contaminated forage.

In sludges, metals exist in various forms (exchangeable, adsorbed, organically bound, carbonates, sulfides, etc.), and availability to crops is a function of the metal form. Metal availability is also influenced by soil properties, and results of studies with southern soils showed metal availabilitity is inversely proportional to soil pH and the concentration of organic matter and oxides of aluminium (Al) and iron (Fe) in the soil. Downward movement of metals in soil is slight and watershed studies have shown little or no increased concentrations of metals in rainfall runoff from sludge application sites.

Analysis of several types of sludges from the South showed a wide variation in median metal values (Table 1.3).

TABLE 1.3

Median concentrations of metals in sludges from the South.[a]

	Pb	Zn	Cu	Ni	Cd	Cr	Hg
	mg/kg						
Municipal sludge	335	1750	475	37	11	380	5
Textile sludge	135	940	416	40	4	1830	—
Fermentation sludge	6	40	13	18	<1	10	—
Wood processing waste	36	73	58	60	<1	30	—

[a]See Appendix Tables 1 and 2 for additional information.

Salts

Application of municipal sludges at rates to supply the nutrient needs of the crop (agronomic rates) normally will not cause a buildup of salts in the soil. However, in arid areas of Texas and Oklahoma, and on sites receiving industrial wastes high in salts, crops may suffer from salt damage. Sodium (Na) salts pose an additional hazard because excessive Na in the soil can cause deterioration of soil structure and thus reduce permeability.

Salts added in wastes, such as manures and sewage sludges, can be handled best by monitoring total salts applied and build up of salts in the soil profile with rate of application and time. Prevention of salt problems is an easier and safer approach than risking the need for soil reclamation.

Management

Once a site is in operation, it must be managed to assure acceptable crop yields, minimize the effect on the environment, and prevent nuisance problems. Runoff and erosion must be controlled using good soil conservation practices. Odor problems can be prevented or minimized by proper sludge stabilization, immediate incorporation or injection, and application when weather conditions will dissipate odors.

The sludge producer is responsible for sludge storage during periods when weather or the cropping system prevent transportation to the site or application. The farmer is responsible for crop and soil management following application.

The scheduling of sludge application is dependent upon weather, soil conditions and cropping schemes. The South can expect periods of high rainfall when it might be impossible to apply sludge. Certain soil types may also limit land application. The application method will depend on sludge solids content and the objectives of sludge utilization.

One of the most critical aspects of managing land application of municipal and industrial sludges is the monitoring and records program maintained for the given site. Monitoring intensity will depend on the frequency and rate of sludge application, the constituents of concern in the sludge, and whether or not the site is dedicated to long-term sludge application. Accurate and detailed records of all analyses, application dates, and application rates must be maintained during the active period of the site and for several years following the last application. Analysis of crops and surface and groundwater will be necessary only for sites receiving sludge at rates greater than agronomic rates.

Use in Land Reclamation

Sewage sludge is particularly useful in the reclamation of surface mined areas, sand tailings piles, borrow pits, and other disturbed land areas. These sites are devoid of organic matter, very low in N, possibly low in pH and in P and K, and have poor physical structure. Almost any non-toxic material which adds organic matter and plant nutrients will have beneficial effects on such sites.

Guidelines and Regulations

Use of sludge on agricultural land is subject to certain restrictions. The U.S. Environmental Protection Agency (EPA) has developed regulations on Cd loading rates and guidelines for rates of application of N, Zn, Cu, Ni, and Pb. Various states have developed their own guidelines. With most sludges these guidelines are easily met and use of sludge on agricultural land is an accepted utilization/disposal method.

Most southern states have developed criteria and management plans for environmentally sound implementation of sludge application to land. For the most part, states have drawn from federal guidelines and recommendations, and most regulations and laws are in the preliminary rather than final form. At present, only Florida, Kentucky, Louisiana, Oklahoma, Texas, and Virginia have well-defined rules as part of their solid waste management policy. Alabama, Arkansas, Georgia, Tennessee, Mississippi, and North Carolina have published guidelines only.

Several states have based their guidelines on rates of N release measured in the Midwest, but these rates would likely be accelerated in the South. The higher release rates must be used when determining N utilization rates.

Generally, factors to be considered for site approval include slope, depth of groundwater, and proximity to surface waters, private wells, dwelling, etc. Most states require monitoring of sludge for N and heavy metal content. North Carolina and Oklahoma require the EPA extraction procedure toxicity test to determine whether the sludge is a hazardous waste. Most states also require some type of soil monitoring, with pH being an important parameter. Although analysis of the crop is not generally required, most states do require some water monitoring. Some states prohibit the use of sludge which exceeds specific concentrations of heavy metals. Most use the EPA guidelines for maximum cumulative heavy metal loading. Application to certain crops is prohibited because of potential pathogen and heavy metal hazards.

Injection or immediate incorporation is generally recommended and annual loading rates are usually based on the N requirement of the crop or the allowable annual Cd loading rate. All states require limited public access to sludge-treated land for a period of one year.

Much of the research from which the EPA developed guidelines was conducted in the Midwest and other areas outside the South. Since the climate and soils in the South are quite different from those in other areas of the U.S., research on sludge use in the South has been needed. This bulletin summarizes the result of sludge research in the South and develops some suggested management procedures. It is not intended to be used as a guide for sludge application. Rather it is intended as a resource for those developing or revising guidelines or designing sludge application systems.

Chapter 2

Macronutrients in Municipal and Industrial Sludges and Crop Response to Sludge Applications

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Application of sludges is beneficial to agricultural soils in several ways. The greatest benefit is the N and P provided for crop nutrition. Sludge also supplies organic matter which improves the physical properties of soil and micronutrients which may or may not be needed.

This chapter summarizes current knowledge on content and availability of nutrients in sludges from the southern United States and the effect of sludge additions on yields under field conditions. The emphasis is on application of sludge at agronomic rates to supply the N and P requirements of the crop rather than excessive rates which may cause heavy metal toxicities in crops (see Chapter 3) and pollution of groundwater by nitrate (Brockway and Urie, 1983; Chaney, 1980a; King and Morris, 1972b, 1972c, 1974; King et al. 1977; Sommers, 1980).

Sludge Characterization

Composition

Nineteen studies of municipal sludges from 45 sites in seven southern states show enormous variability in composition (see Appendix Table 1). Data on solids, ash and macronutrients are summarized in Table 2.1.

Because composition varies greatly, each sludge intended for use on agricultural land should be analyzed separately. N and P are found at adequate levels in most sludges analyzed, Ca is usually adequate, but levels of K and Mg are low. Concentrations of all nutrients in sludges from southern states are lower than those found in sludges from the Midwest.

Composition of industrial wastes has also been determined by source: textile mills, fermentation processing, poultry processing, wood processing, and refinery/petrochemical (see Appendix Table 2). Data on solids, ash, and macronutrients are summarized by source in Table 2.2.

TABLE 2.1

Properties of municipal sludges from several southern states.[a]

	Number of samples	Range	Mean	Median[b]
Solids content of liquid sludges (%)	13	0.6-7.1	3.8	4.4
Ash (% of solids)	16	19-59	43.0	47.0
pH	8	5.4-7.0	6.1	5.9
Total N of solids (%)	21	0.6-7.5	3.0	2.6 (3.3)
Total N[c] of liquid fraction (mg/L)	13	7-730	280	290
Total P of solids (%)	40	0.4-5.3	1.8	1.6 (2.3)
Total K of solids (%)	40	<0.1-1.0	0.2	0.2 (0.3)
Total Ca of solids (%)	39	<0.1-6.0	1.5	1.3 (3.9)
Total Mg of solids (%)	39	0.1-0.5	0.2	0.2 (0.45)

[a]See Appendix Table 1 for additional data.
[b]Data in ( ) is for sludges mainly from the midwestern US (from Sommers, 1977).
[c]Predominantly NH_4^+-N.

TABLE 2.2

Properties of industrial wastes from several southern states.[a]

	Textile sludges				Fermentation sludges				Wood processing wastes			
	No. of samples	Range	Mean	Median	No. of samples	Range	Mean	Median	No. of samples	Range	Mean	Median
Solids content of liquid wastes (%)	5	0.6-13.5	6.0	6.9	4	13-54	26	19	1	—	—	12.4
Ash (% of solids)	9	14-76	41	43	3	37-66	51	49	5	6-67	40	45
Total N of solids (%)	9	1.0-7.9	4.1	2.8	6	2.0-7.0	4.1	3.5	6	0.3-2.3	0.8	0.4
Total N[b] of liquid fraction (mg/L)	5	16-112	42	22	3	19-680	350	340	0	—	—	—
Total P of solids (%)	9	0.3-2.0	1.1	0.9	5	0.1-0.7	0.4	0.2	5	<0.1-0.3	0.1	0.1
Total K of solids (%)	9	0.1-0.3	0.2	0.2	5	<0.1-0.2	0.1	0.1	5	<0.1-9.3	1.9	0.1
Total Ca of solids (%)	9	0.1-0.8	0.5	0.5	5	<0.1-9.8	4.5	5.2	5	0.3-9.8	3.3	0.8
Total Mg of solids (%)	9	0.1-0.4	0.2	0.2	5	<0.1-0.2	0.1	<0.1	5	<0.1-0.7	0.2	0.1

[a]See Appendix Table 2 for additional data.

[b]Predominantly NH_4^+-N

The N content of textile and fermentation wastes is generally comparable to that of municipal sludge, but N content of wood processing wastes is considerably lower. With the exception of Ca in fermentation wastes, and of Ca and K in wood processing wastes, concentrations of other macronutrients are relatively low.

Nutrient Availability to Crops

Determining total concentration of nutrients in sludges is relatively easy, but estimating the nutrients actually available to crops is much more difficult. However, the available nutrient content is more important than total concentration because this value determines loading rates.

Several methods can be used to estimate nutrient availability. Laboratory incubation studies have been used for many years to estimate the availability of nutrients (particularly N) in organic materials. Since these studies require up to 16 weeks to conduct, rapid chemical tests have been used, but with mixed success (Castellanos and Pratt, 1981; Magdoff and Amadon, 1980; Parker and Sommers, 1983). In addition, greenhouse or field tests can be conducted in which nutrient budgets are developed so availability can be estimated.

Note that when recovery of applied nutrients is reported in this bulletin, either as crop removal or accumulation in the soil, recovery in the non-treated control has always been deducted before calculating percent recovery.

Nitrogen

Soil incubation was used to estimate availability of organic N in municipal and industrial sludges from several southern states (Table 2.3). In municipal sludges, organic N availability was highest in liquid aerobically digested sludges (median 27%) and lowest in dried anaerobically digested dried sludges (median 14%). Although no composted sludges were included in the study, composting has been shown to lower N availability (Parker and Sommers, 1983). Availability of N in textile and fermentation sludges was relatively high, but paper mill sludges caused N immobilization rather than a net mineralization of N.

The wide range of availability within a particular sludge grouping indicates the need to assess N availability for each sludge to be used on agricultural land. Also, since soil type can dramatically affect N availability (Chescheir, 1984; King, 1979, 1981), incubation studies should be conducted with soils from the site where the sludge is to be applied.

A greenhouse study determined the effect of waste wood fiber containing urea-formaldehyde on yield and

TABLE 2.3

Availability of organic N in municipal and industrial sludge from the southern US[a] (King, 1973, 1984; King and Vick, 1978; Simpson et al., 1983).

Material	Number of samples	Range	Mean	Median
	--------- *% of initial organic N available* ---------			
Municipal sludges				
Aerobically digested				
Solids from liquid sludge	3	26 to 39	31	27
Anaerobically digested				
Solids from liquid sludge	3	20 to 30	24	21
Solids from drying beds	5	4 to 18	12	14
Textile sludges	4	9 to 47	27	26
Papermill sludges	5	−45[b] to 35	−25	−17
Fermentation sludges	3	24 to 61	42	39

[a]Samples of sludge were incubated with soil under laboratory conditions for 16 to 18 weeks.

[b]Negative values indicate N immobilization.

composition of fescuegrass growing in soil from a Cecil (Typic Hapludults) Ap horizon (sandy loam) and B horizon (clay loam) (King, 1979). Initially, yields with wood fiber were high, but they declined and after 15 months were comparable to yields in the control treatment. By that time fescue had recovered 30% of the applied N from the Ap horizon and 17% from the B horizon.

In a similar greenhouse study with liquid anaerobic sewage sludge, recovery of sludge-applied N by fescuegrass was 24% when the sludge was surface-applied and 16% when it was incorporated into the soil after surface application and drying (King, 1981).

Lower recovery with incorporation suggests appreciable denitrification induced by sludge addition as has been shown in sludge incubation studies (King, 1973; Ryan et al., 1973). Soil from Norfolk (Typic Paleudults) and Cecil Ap horizons were used. Recovery from the Norfolk was 23%, but that from Cecil was only 17%.

These studies show the significance of the effects of soil type on N availability and the importance of method of application.

In an Alabama field study, aerobically digested liquid sludge supplied 11 metric tons (mt)/ha of dry solids to a Decatur silt loam (Rhodic Paleudults) for corn production (Giordano and Mays, 1981). Of the 275 kg/ha of total N applied, 33% was recovered in the corn grain and 8% in the soil as nitrate-N the first year. Stover yield and composition were not reported, but if one uses the estimate that the same quantity of N was recovered in the stover as in the grain, the total first year recovery of sludge-applied N would be 74%.

Continuation of the study an additional two years showed continued high corn yields with no additional sludge application (Giordano and Mays, 1983). If one assumes that the N concentration in the grain was constant for the 3-year period, then 70% of the sludge-applied N can be accounted for in the grain. Inclusion of N recovered in stover the third year would further increase percent recovery.

In a similar study in North Carolina, aerobically digested liquid sludge was applied to a Wedowee sandy loam (Typic Hapludults) for corn production.[1] At the end of the first growing season, 20 to 25% of the applied N was accounted for in the corn grain, stover, and the increased quantity of soil nitrate in the top 120 cm of the soil profile. For treatments receiving sludge the second year, recovery for the 2-year period was 21%, but in a residual treatment not receiving a second sludge application, 2-year recovery was 38%. Recovery from treatments receiving a third sludge application averaged 26% for the 3-year period, but recovery from the residual treatment was 52% for the 3-year period. It was hypothesized that the available C supplied by the second and third sludge additions, plus wet conditions during the second year, resulted in substantial denitrification.

A study of liquid sludge surface-applied to a Cecil clay loam soil for Coastal bermudagrass production was conducted in Georgia in 1969 and 1970 (King and Morris, 1972a, 1972c). When sludge was applied at rates to supply 22 or 44 mt/ha of solids per year, 23% of the applied sludge N could be accounted for in the harvested grass over the 2-year period. The residual effect of sludge was determined in 1971 and part of the 1973 growing season (Touchton et al., 1976). Although grass N content was not determined, if one assumes (a) the same N content during the residual period as in 1969 and 1970 and (b) yield in 1972 was equal to that in 1973, then approximately 46% of the applied N can be accounted for by crop harvest.

In a 2-year study in North Carolina, filter presscake from citric acid production was surface-applied to a Kureb sand (Spodic Quartzipsamments) for Coastal bermudagrass production (King, 1980). An average of 21% of the applied N was accounted for in grass harvested during the 2-year period plus increased soil nitrate measured at the end of the second year. Since nitrate leaching below the sampled depth during the first year was not quantified, the actual N availability was higher than the 21% measured. In a laboratory incubation study with the same soil and presscake, 28% of the applied N was present as nitrate at the end of 32 weeks (King and Vick, 1978).

Phosphorus

In contrast to N, the majority of the P in sewage sludges appears to be in the inorganic form. For example Sommers et al. (1976) found the inorganic P content of eight Indiana sludges averaged 73% of the total P content. The availability of sludge P to plants depends both on the rate at which it becomes available from the sludge and the rate at which it reacts with the soil to form unavailable compounds.

Taylor et al. (1978) incubated composted sludge with sand and several soils with varying P-fixing capacities. The availability of P from compost only was estimated as the Bray-P_1 (0.03 N NH_4F in 0.025 N HCl) extractable P from the sand-compost mixture. Seventy percent of the total P was extracted initially and extractability did not change appreciably with time. Extractability was lower in soil-compost mixtures ranging from 40% in a loamy sand to 8% in a clay soil. Extractability fluctuated with time in the soil-compost mixtures, but patterns among soils were not consistent. Tester et al. (1979) found no effect of length of incubation period on Bray-P_1, extractable P from a sludge-compost-amended loamy sand (Typic Quartzipsamments) incubated for 48 weeks.

Greenhouse studies in Florida (Hortenstine and Rothwell, 1968) and Alabama (Shuford et al., 1982) showed increased concentration of Mehlich 1 (0.05 N HCl + 0.025 N H_2SO_4) extractable soil P and increased P concentrations in crops from sludge-amended soils.

[1]Unpublished data. L. D. King. Dept. of Soil Science, N.C. State University, Raleigh, NC.

In the Alabama field study with sludge on corn, 10% of the applied P was recovered in corn grain the first year (Giordano and Mays, 1981). Mehlich 1 extractable soil P accounted for 87% of the applied P. If P recovery in the stover had been included (data not available) then recovery would be greater than 100%. Evidently sludge addition increased availability of native soil P.

In the Georgia study with sludge on Coastal bermudagrass, 12% of the applied P was recovered through hay harvest over the 2-year period (King and Morris, 1973). However, sludge treatments did not increase Mehlich 1 extractable P in the 0- to 15-cm soil layer. The high P-fixing capacity of this soil and its low pH (5.1) combined to render much of the P released from the sludge unavailable (King and Morris, 1972b). Approximately 50% of the applied P remained in the sludge solids which accumulated on the soil surface. The third year after the final sludge application, sludge was still supplying adequate P for grass production as evidenced by the adequate levels of P in the grass (Touchton et al., 1976).

Boswell (1975) applied sludge supplying 138 kg P/ha and commercial fertilizer supplying 94 kg P/ha to fescuegrass on a Davidson clay loam (Rhodic Paleudults) in Georgia. Forage from the sludge-treated plots had higher P content than did forage from the fertilizer plots. However, due to a 50% lower yield, P recovery in the forage was only 20% from sludge P compared to 40% from fertilizer P.

Thangudu et al. (1981) applied sludge to a Byler loam (Typic Fragiudalfs) for corn production in Tennessee. Initial applications supplying up to 1190 kg P/ha did not increase extractable soil P [1% $(NH_4)_2SO_4$ in 0.05 *N* H_2SO_4] above levels where 28 kg P/ha had been applied as commercial fertilizer. After additional applications the second year, extractable P was significantly increased where sludge had applied a total of 1034 and 2067 kg P/ha.

A knowledge of the forms of P found in the soil after sludge application would improve soil management from the standpoint of P availability. Phosphorus in the soil is found in four major forms: organic (Organic-P), iron phosphate (Fe-P), aluminum phosphate (Al-P), and calcium phosphate (Ca-P). When sludge or fertilizers are applied to the soil, the soluble phosphate reacts chemically with the soil components through a series of precipitation and/or adsorption reactions. Where precipitation predominates, one or more of the inorganic forms of phosphate are formed.

Few studies have reported on the phosphorus compounds formed in southeastern soils following land application of sludge. Results from a greenhouse experiment in Alabama with a Hartsell fine sandy loam (Typic Hapludults) indicated that when sludge was mixed at 100 mt/ha with the soil (cropped to soybean and wheat), the pattern of the quantity of phosphate compounds present was organic-P > Fe-P > Al-P > Ca-P > soluble P (Shuford et al., 1982). Also, the lower the initial soil pH, the greater the quantity of Al-P and Fe-P measured, while the reverse was the case for Ca-P. Soil from the same area and of the same type, amended with sludge for eight years in a garden, had a pattern of Al-P = organic-P > Fe-P > Ca-P > soluble-P.

If a relatively large quantity of sludge P ultimately forms Fe-P, then P will be less available compared to a situation where most of the sludge P is found as Al-P and/or Ca-P (Juno and Ellis, 1968).

The Langmuir adsorption isotherm may be used to determine a theoretical value for the maximum amount of P that a given quantity of soil will absorb (Olsen and Watanabe, 1957). In the field, the downward movement of P may occur if the quantity of P applied greatly exceeds the adsorption maximum value determined by the Langmuir isotherm. Therefore, the soil's P adsorption maximum may be used as a diagnostic tool to determine the maximum quantity of P a soil may accommodate before P leaching becomes a concern.

Very few reports on sludge application to southeastern soils have studied the use of the soil adsorption maximum in the manner mentioned above. However, one study in Alabama on a Hartsells fine sandy loam, in which an unknown amount of sludge was applied to a garden soil for over eight years (Shuford et al., 1982) indicated the following:

1. The residual level of available phosphorus in the soil was extremely high (1472 kg/ha).
2. No P was adsorbed when soil pH was adjusted to 6.4 and 7.0; therefore, no adsorption isotherm was developed.
3. When the soil pH was adjusted to 5.8, additional P was adsorbed and an adsorption isotherm developed.

This study suggests that continuous heavy application of sludge to slightly acid to neutral southeastern soils can result in P saturation of the surface soil with subsequent P movement into the subsoil.

Potassium

Municipal sludges are low in K (Table 2.1), and supplemental K usually must be added to maintain good crop growth (Lutrick et al., 1982). On a Cecil soil in Georgia, sludge rates supplying 60 to 120 kg K/ha resulted in K concentrations in Coastal bermudagrass comparable to or higher than concentrations in grass receiving 93 kg K/ha from commercial fertilizer (King and Morris, 1972a). During the second year, however, at sludge rates supplying up to 272 kg/ha K, grass K concentration dropped below the deficiency level of 1.5% while concentrations with 224 kg/ha fertilizer K were generally above 1.5%. Recovery by crop removal exceeded the quantity applied but approximately 45% of the sludge-applied K remained in the sludge solids which accumulated on the soil surface. Evidently sludge application enhanced availability of native soil K. Residual studies showed a continued decline in forage K content (Touchton et al., 1976).

Giordano and Mays (1981) found that supplemental K is not required initially if levels of soil K are high. On a Decatur silt loam in Alabama, they found no significant difference due to treatments in K concentration of diagnostic plant parts of corn, cotton, and soybeans where K had been applied at 22 kg/ha from sludge or 112 kg/ha from commercial fertilizer.

Summary of Availability Data

Nutrient availability data discussed above is summarized in Table 2.4. Recovery of sludge-applied N varied considerably. Recovery in the Alabama study was particularly high. In the North Carolina study with corn, recovery was high when sludge was applied only once but repeated applications resulted in low recovery.

The recent EPA manual on sludge application to land (Environ. Protection Agency 1983) recommends a procedure for estimating availability of N in sludges. The procedure is based on results of incubation studies with a variety of sludges (Sommers et al. 1981). Ammonium-N is assumed 100% available if sludge is injected and 50% available if sludge is surface-applied. The procedure then assumes a decay series for mineralization of organic N. For aerobically digested sludge the series is 30% the first year and 15, 8, 4, 3 and 3% annually for the following five years. For anaerobically digested sludges the suggested decay series is 20, 10, 5, 3, 3, 3% annually.

For the single 18 mt rate in the North Carolina study with corn, the EPA procedure overestimated availability initially, but was close to actual availability after 3 years (Table 2.4). Annual applications of 9 mt/ha resulted in much lower availability than predicted by the EPA procedure. With anaerobically digested sludge applied to Coastal bermudagrass in Georgia, the EPA procedure overestimated N availability initially and underestimated it at the end of five years.

Recovery of sludge-applied P by crop uptake was variable, but recovery as extractable soil P was much more variable (Table 2.4). Potassium recovery was always greater than 100% because of the small amount of K supplied by sludge.

Effect of Dewatering on Composition and Availability

All municipal sludges and many industrial sludges originate as liquids, and various types of dewatering methods are available if a thicker liquid sludge or a solid sludge is desired. Data in Figure 2.1 show the effect of dewatering on the total amount of "recoverable" plant available N (PAN) produced by a wastewater treatment facility, the volume of sludge, and the PAN content of the sludge. The figure was developed from the median sludge in Table 2.1, assuming complete availability of N in the liquid fraction and 30% availability of the organic N in the solids, and assuming a sludge flow of 380,000 L/day at 4.4% solids.

During dewatering some sludge PAN is lost since soluble N is removed with the liquid fraction. (The liquid is cycled back to the inflow of the treatment plant.) However, the total loss of PAN is not large, e.g. a 7% loss in PAN when sludge is dewatered to 18% from 4.4% solids (Fig. 2.1). The quantity of sludge drops dramatically as water is removed. As the solids content increases, the PAN increases (in this case 0.29 kg PAN per 1000 L for each 1% increase in solids content.)

In liquid sludge the ratio of N in the liquid fraction to N in the solid fraction is relatively high compared to the ratio for other nutrients (King and Morris, 1972a). Consequently, the concentration of these other nutrients will rise faster than the rise in PAN concentration as solids content increases.

The net effect of dewatering is to reduce sludge volume with a minimal "loss" of nutrients and to improve the sludge for agronomic use by increasing nutrient concentration.

Crop Response

From an agricultural standpoint, one of the most significant factors in utilization of sludge is its effect on crop yields. The agronomic effects of sludges can be demonstrated by comparisons of yields from sludge application with those obtained with commerical fertilizer. Results of several such comparison experiments are summarized in Table 2.5 and discussed below.

Giordano and Mays (1981, 1983) compared liquid sewage sludge with commercial fertilizer for production of corn, cotton, and soybeans on a Decatur silt loam in Alabama. Cumulative yields over a 4-year period (3 years for cotton) were greater from a single application of 11 mt/ha sludge solids (275-209-22 kg/ha NPK) than from annual applications of 168-45-112 kg/ha NPK from commercial fertilizer.

Lutrick et al. (1982) compared five rates of liquid sludge with commercial fertilizer for corn, soybeans and grain sorghum production on Orangeburg, Troup and Lucy fine sandy loams (Typic, Grossarenic, and Aeric Paleudults, respectively) in Florida. Over a 6-year period 87 mt/ha of sludge solids were applied by the low rate (3180-1270-100 kg/ha NPK). Sludge treatments received an additional 112 kg/ha K as KCl the last four years. Separate fertilizer treatments supplied 294-55-110 kg/ha per year NPK to corn and grain sorghum and 0-65-60 kg/ha per year NPK to soybeans.

Sludge significantly decreased corn yields two years and had no significant effect three years. No corn was harvested one year due to dry weather. Grain sorghum yields were not affected by sludge two years. In other years, with the low sludge rate yield was equal to or less than yield with commercial fertilizer but with higher rates (up to a total of 241 mt/ha) yields were increased. Soybean yields were either not affected or depressed by sludge applications.

TABLE 2.4

Recovery of sludge-applied nutrients by crop harvest and accumulation in the soil profile.

State	Sludge: Type	Sludge: Cumulative quantity	Nutrients applied: N	P	K	Crop	Years applied	Residual years	N recovered: Crop	Soil	Total	P recovered: Crop	Soil	Total	K recovered: Crop	Soil	Total	References
		mt/ha	------ *kg/ha* ------						------ *% applied* ------									
AL	Aerobically digested, municipal	11	275	209	22	corn	1	0	33[a]	8	41	10	87	97	127	0	127	Giordano and Mays 1981, 1983
		11	275	209	22	corn	1	2	70[b]	—	70	—	—	—	—	—	—	
NC	Aerobically digested, municipal	18	1290	350	65	corn	1	0	5	14	19 (40)[c]	—	—	—	—	—	—	King, unpublished data
		18	1290	350	65	corn	1	1	24	22	46 (49)	—	—	—	—	—	—	
		18	1290	350	65	corn	1	2	14	38	52 (53)	—	—	—	—	—	—	
		9	645	175	30	corn	1	0	9	16	25 (40)	—	—	—	—	—	—	
		18	1300	380	60	corn	2	0	7	14	21 (44)	—	—	—	—	—	—	
		27	1970	560	90	corn	3	0	7	17	24 (47)	—	—	—	—	—	—	
GA	Anaerobically digested, municipal	87	3058	765	220	coastal	2	0	23	0	23 (30)	12	0	12	205	—	—	King and Morris, 1972a, 1972b; Touchton et al., 1976
		87	3058	765	220	bermudagrass and rye	2	3	46[b]	0	46 (38)	—	—	—	—	—	—	
GA	Anaerobically digested, municipal	17	378	138	20	fescuegrass	2	0	—	—	—	20	—	—	130	—	—	Boswell, 1975
NC	Citric acid	51	1120	157	32	coastal bermudagrass and rye	2	0	17	4	21	—	—	—	—	—	—	King, 1980

[a]Grain only.

[b]Estimated, see text.

[c]Values in ( ) are estimated availability based on the system suggested by EPA (1983).

TABLE 2.5

Summary of yield response to sludges and commercial fertilizer

State	Type	Sludge: Cumulative quantity	Sludge: Nutrients applied[a] N	P	K	Commercial fertilizer[b] N	P	K	Crop	Length of study	Cumulative yield: No treatment	Commercial fertilizer	Sludge	References
		mt/ha	*kg/ha*							*years*	*mt/ha*			
AL	Municipal	11	275	209	22	168	45	112	corn	4	12	21	24	Giordano and Mays, 1981, 1983
									soybeans	4	9	10	13	
									cotton	3	6	10	8	
FL	Municipal	87	3180	1270	100	1760	330	660	corn	5	—	18	16	Lutrick et al., 1982
					(448)	1760	330	660	grain sorghum	6	—	24	23	
						0	390	360	soybeans	6	—	15	15	
GA	Municipal	61	820	530 (20)	122 (74)	217	20	74	corn	1	5	10	11	Sims and Boswell, 1980
NC	Papermill													
	primary	106	668	189	347	176	48	100	corn	1	5	8	7	Simpson et al., 1983
	secondary	53	446	170	215	176	48	100	corn	1	5	8	7	
NC	Municipal	27	1890	600	99 (30)	504	0	30	corn	3	5	11	14	King, unpublished data
AL	Municipal	20	320	860	2	R	R	R	sudangrass	1	5	8	7	Shuford et al., 1982
		60	1160	1580	12	R	R	R	barley	3	4	6	7	
NC	Citric acid presscake	27	204	17 (49)	24 (93)	168	49	93	corn	1	1	4	4	King, unpublished data
NC	Citric acid presscake	51	1120	157 (237)	32 (279)	1120	80	279	coastal bermuda + rye	2	3	18	16	King, 1980
GA	Municipal	87	3058	765	220	1200	300	700	coastal bermuda + rye	5	11	58	59	King and Morris, 1972a, 1972b; Touchton et al., 1976
GA	Municipal	17	378	138	20	448	188	404	fescue	2	10	24	12	Boswell, 1975

[a]Values in ( ) are supplemental quantities of nutrient supplied by commercial fertilizer.
[b]R = Recommended amount from soil test applied. Quantity not reported.

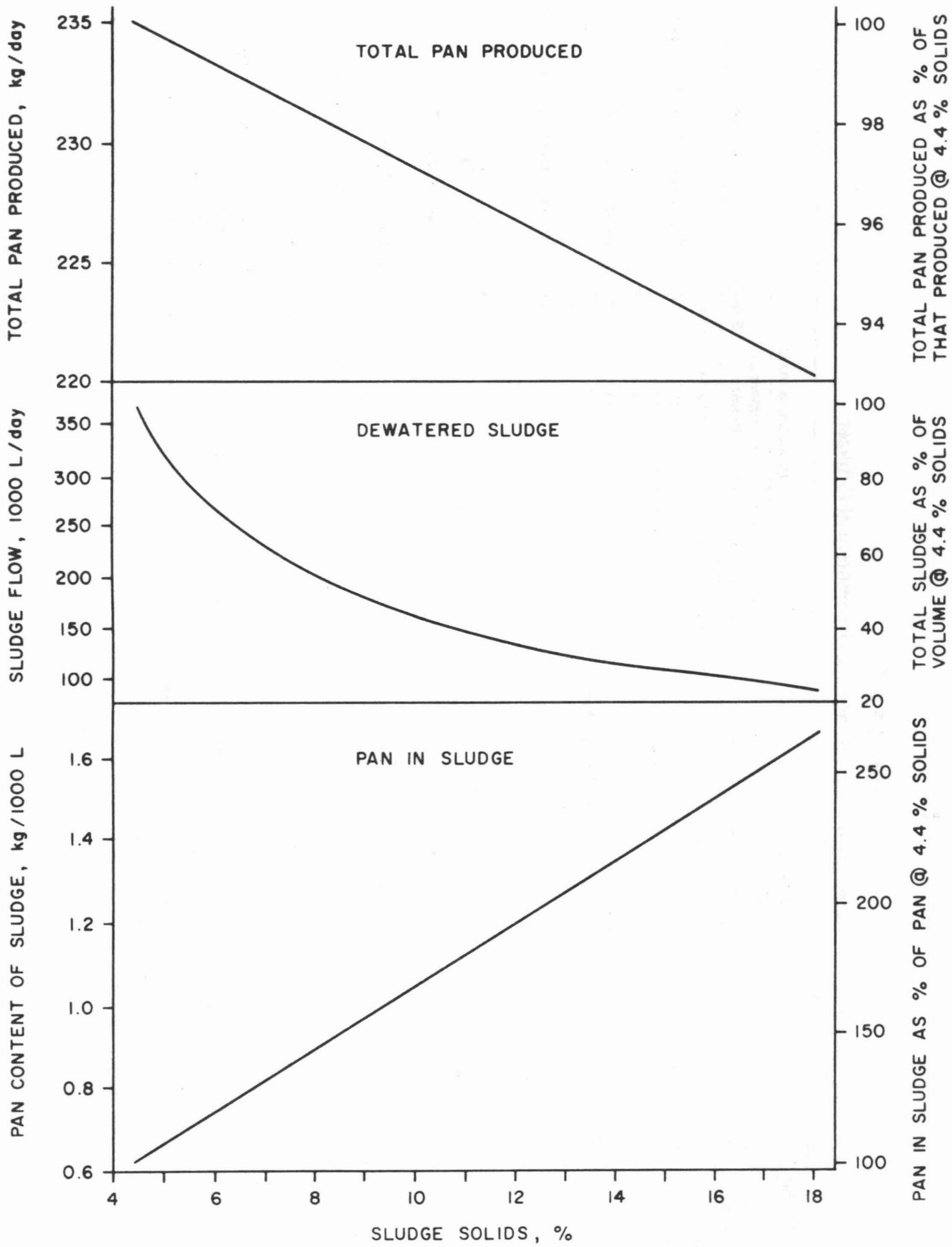

Figure 2.1 Effect of dewatering on sludge properties (PAN = plant available nitrogen).

Sims and Boswell (1980) compared 61 mt/ha per year dry sludge (820-530-122 kg/ha per year NPK) with 271 kg N/ha per year from NH_4NO_3 for corn production on a Cecil soil in Georgia. All treatments were supplemented with 0-20-74 kg/ha per year NPK. Due to drought and army worm damage, yield was low the first year and data were not reported. The second year corn grain yield was increased 36% by NH_4NO_3 and 73% by sludge as compared to yield from the control treatment receiving no N.

Mixtures of papermill sludge and fly ash were compared with commercial fertilizer for corn production on a Cordorus loam (Fluvaquentic Dystrochrepts) in the mountains of North Carolina (Simpson 1980, Simpson et al., 1983). A 2:1 fly ash-primary sludge mixture at 106 mt/ha (668-189-347 kg/ha NPK), 2:1 fly ash-secondary sludge at 53 mt/ha (466-170-215 kg/ha NPK), and commercial fertilizer (176-48-100 kg/ha NPK) produced equivalent yields which were 44% higher than yield with no amendments. Higher rates of fly ash-sludge and fertilizer did not result in additional yield increases. Fall application was as effective as spring application.

Aerobically digested liquid sludge was compared with commercial fertilizer for corn production on a Wedowee soil in a 3-year study in North Carolina[1]. Sludge at 9 mt/ha per year solids (630-200-33 kg/ha per year NPK) and 18 and 27 mt was compared with 84 and 168 kg/ha per year N from NH_4NO_3. Supplemental K (30 kg/ha) was added to all treatments the first year only. Over the 3-year period yields were comparable with spring- and fall-applied sludge and surface application was superior to injection. Yields were not affected by sludge rates in the fall. Spring-applied sludge rates greater than 9 mt/ha were generally superior to the higher NH_4NO_3 rate. The highest cummulative yield was produced by 18 mt/ha applied the first year only.

In a study on a Decatur silt loam in Alabama, Shuford et al. (1982) compared sludge at 20 mt/ha per year dry solids (an average of 370-610-4 kg/ha per year NPK) with commercial fertilizer applied at rates based on soil test results (quantity not reported). Comparable yields of sudangrass were obtained with sludge and fertilizer and were 38% higher than yields with no amendments. Barley yields were higher with sludge than with fertilizer the first two years, but were not significantly different the third year.

Filter presscake from citric acid production was compared with commercial fertilizer for corn production on an Ogeechee loamy sand (Typic Ochraquults) in the Coastal Plain of North Carolina.[1] Twenty seven metric tons/ha (204-17-24 kg/ha NPK) supplemented with 0-49-93 kg/ha NPK from commercial fertilizer were as effective in increasing corn yield as was commercial fertilizer (168-49-93 kg/ha NPK). Higher presscake rates did not result in additional yield increases.

The same presscake was also applied to Coastal bermudagrass overseeded with rye in the fall on a Kureb sand (King 1980). With one year of application and one residual year, yield with 38 mt/ha presscake (794-113-283 kg/ha NPK) was comparable to 740-64-273 kg/ha NPK from commercial fertilizer in increasing total yield. In a second study presscake was applied in five applications per year to supply 48 mt/ha per year (490-27-27 kg/ha per year NPK plus 67 kg/ha per year P from commercial fertilizer). Yields with presscake and fertilizer were comparable.

Four rates of liquid sludge were applied to a Cecil soil in the Georgia Piedmont for production of Coastal bermudagrass overseeded with rye in the fall (King and Morris 1972a, 1972b; Touchton et al., 1976). Over a 2-year period, a total of 44 mt/ha of sludge solids was applied at the low rate (1530-382-110 kg/ha NPK). Cumulative yield with this sludge rate over a 5-year period was 70% of the yield with annual applications of commercial fertilizer, totaling 1200-300-700 kg/ha NPK. Sludge applied at 87 mt/ha produced a cumulative yield equal to that produced with fertilizer. Higher sludge rates did not result in additional yield increases.

Boswell (1975) compared dry sludge with commercial fertilizer for fescue production on a Davidson clay loam in Georgia. Sludge at 5.6 mt/ha (378-138-20 kg/ha per year NPK) did not significantly increase yields but commercial fertilizer supplying 224-94-202 kg/ha per year NPK increased yields 250%.

Berry and Marx (1977) studied the use of sludge to revegetate kaolin mine spoil in Georgia. Sludge decreased survival of pine seedlings, but rates up to 69 mt/ha (1480 kg/ha N) resulted in 81% survival and increased height, diameter, fresh weight, and degree of ectomycorrhizol development on the seedling roots.

The data in Table 2.5 show that yields with sludge applications are equal to or greater than yields produced with commercial fertilizer applied at recommended rates. Since N is the plant nutrient that usually most limits crop growth, response to sludge was most likely a response to sludge-supplied N. With municipal sludges the ratio of sludge N to fertilizer N required to produce approximately equal yields ranged from 1.6 to 3.8 and averaged 2.7. The ratios were 3.8 and 2.6 for primary and secondary papermill sludges, respectively. For citric acid presscake the ratio averaged 1.1.

Conclusions

The variability in nutrient availability and crop response under field conditions indicate that we are not yet able to recommend sludge application rates very accurately. The best approach is to make the initial sludge application at a rate based on the best available data for the particular sludge and the site. Plant tissue should be sampled and analyzed during the growing season, and the results used to determine if nutrients are present in deficient, sufficient or excess concentrations. At the end of the growing season soil samples should be taken to determine if excess concentrations of inorganic N are present and thus pose a groundwater pollution hazard. These samples can also be used for standard soil testing to determine the status of other plant nutrients in the soils. Adjustments can then be made in sludge or supplemental fertilizer rates the following year.

[1]Unpublished data. L. D. King. Dept. of Soil Science, N.C. State University, Raleigh, NC.

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Chapter 3

Effect of Sludges on Heavy Metals in Soils and Crops

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As shown in Chapter 2, application of sludge to agricultural land is beneficial mainly because of the N and P supplied for crop nutrition. However, sludges contain varying amounts of heavy metals that may pose a hazard of metal toxicity in crops and to consumers of the crops. Copper, Zn, and Ni are the metals most likely to cause toxicity in crops, but they do not pose a health hazard because the concentrations that cause toxicity in plants do not cause toxicity in animals or humans consuming the crop. However, Cd can accumulate in plants to concentrations that would be toxic to consumers of the plants but not to the plants themselves. Therefore, sludge applications must be adjusted to minimize the entrance of Cd into the food chain. When sludge is applied at a rate to supply only the N requirement of the crop, heavy metal loading rates are generally low and do not pose a hazard to crops, animals or humans.

Various studies have shown little or no increase in crop uptake of Cr and Pb as a result of sludge additions (Mortvedt and Giordano, 1975; Giordano et al., 1975; Sims and Boswell, 1976; King, 1981). The most probable route of entry of these elements into the food chain from sludge would be from surface-contaminated crops or, since grazing animals ingest significant amounts of soil, direct ingestion by grazing animals of sludge on the surface of the soil (Boswell, 1975; Chaney and Lloyd, 1979; Healy, 1968). Since actual crop uptake of Pb and Cr is minimal, these elements will not be covered in this review.

Ryan et al. (1982) conducted an extensive literature review on the health effects of Cd in the food chain. They found that although insufficient evidence is available to link Cd with cancer, renal tubular damage and pulmonary emphysema are associated with excessive Cd exposure. For people not occupationally exposed to Cd, the main route of exposure is through food and tobacco smoke. Since Cd accumulates in the liver and kidney rather than in muscle or milk (Anderson et al., 1982; Bray et al., 1985; Baxter et al., 1980, 1982, 1983; Dowdy et al., 1983; Fitzgerald, 1980; Williams et al., 1978), the movement of Cd from soil to plant to animal to humans is not a concern if these organs are not eaten. However, if the "animal filter" is removed from the chain, then increased Cd intake might result from direct ingestion of plants grown on sites with elevated Cd concentrations. The degree of risk depends on the amount of the diet that is affected, the makeup of the diet, the concentration of soil Cd, and the soil pH.

Ryan et al. (1982) also reported that current Cd intake rate via ingestion is approximately 38 μg/day with about 5% of this being absorbed by the body. Inhaled Cd is adsorbed much more efficiently than is ingested Cd. For example, 50 to 67% of the Cd in cigarette smoke is absorbed and the Cd content of kidneys of smokers is approximately double that of non-smokers. In the U.S. the mean Cd concentration in the renal cortex is 20-35 mg/kg with only 0.6% of the population exceeding 100 mg/kg. When Cd in the renal cortex reaches 200 mg/kg, the first signs of renal dysfunction are usually observed (proteins in the urine). Various metabolic models have been used to estimate the daily Cd intake rate required to result in 200 mg/kg Cd in the renal cortex. For nonsmokers, a daily consumption of 200 μg is a reasonable estimate of lifetime ingestion which would result in a critical concentration in the renal cortex. For smokers the 200 μg value should be reduced by 25 μg for each pack of cigarettes smoked per day.

Sludge Characterization

The composition of municipal and industrial sludges from several southern states is presented in Appendix Tables 1 and 2. Heavy metal content is summarized in Table 3.1. Median values for Zn, Cd, and Hg in municipal sludges are similar to values in sludges from the midwestern U.S. but values for Pb, Cu, Ni, and Cr are lower. With the exception of Cr, the heavy metal content of textile sludges is lower than that of municipal sludges. Since fermentation sludges result from production of food grade products, the heavy metal content of

TABLE 3.1

Heavy metal content of municipal sludges and industrial wastes from several southern states.[a]

	Municipal sludges				Textile sludges				Fermentation sludges				Wood processing wastes			
Metal	No. of samples	Range	Mean	Median	No. of samples	Range	Mean	Median	No. of samples	Range	Mean	Median	No. of samples	Range	Mean	Median
	mg/kg				mg/kg				mg/kg				mg/kg			
Pb	39	70-2,750	520	335 (500)[b]	9	9-250	129	135	5	<1-95	29	6	6	<1-90	42	36
Zn	41	620-21,000	2,960	1,750(1,740)	9	40-1,800	864	940	5	5-975	255	40	6	25-337	122	73
Cu	41	147-6,320	980	475 (850)	9	149-760	390	416	5	3-210	81	13	6	<1-91	53	58
Ni	37	11-954	100	37 (82)	9	31-155	63	40	4	<1-34	18	18	6	6-492	119	60
Cd	39	<1-165	28	11 (16)	9	<1-9	4	4	5	<1-3	2	<1	6	<1-4	2	<1
Cr	36	53-13,600	1,040	380 (890)	9	41-5,560	2,490	1,830	5	<1-540	117	10	6	<1-362	81	30
Hg	3	3-8	5	5 (5)	—	—	—	—	—	—	—	—	—	—	—	—

[a]See Appendix Tables 1 and 2 for additional data.

[b]Data in ( ) are from Sommers (1977) for municipal sludges mainly from the midwestern US.

TABLE 3.2

Distribution of metals in several sludges from Indiana (Stover et al., 1976).

	Estimated metal fraction					
Metal	Exchangeable	Adsorbed	Organically bound	Carbonates	Sulfides & other species	Total recovery
	% of total metal in sludge					
Cd	0	0	15	49	18	82
Cu	6	10	10	23	35	84
Zn	0.3	0.4	50	18	9	79
Ni	14	8	14	32	7	75
Pb	0	9	29	61	4	103

these sludges is low. Wood processing wastes are also low in metal content. Variation of metal content of these various wastes stresses the need for characterization of each material intended for use on agricultural land.

Heavy metals in sludges may exist as soluble, exchangeable, organic, adsorbed, and precipitated forms (Lake et al., 1984). The distribution of the metals among the various forms is dependent on properties of the specific metal and the characteristics of the sludge. For example Cd and Zn are adsorbed on surfaces of hydrous oxides of Fe and Al and would probably coprecipitate with these compounds during sewage treatment (Sommers, 1980). Stover et al. (1976) used sequential extraction procedures to estimate the distribution of metals in several sludges from Indiana. Mean values are shown in Table 3.2. The availability of a specific metal for crop uptake is determined by its distribution among the various forms in the sludge.

Heavy Metals in Soils

Since agricultural use of sludges will cause an increase in heavy metal content of soils and crops, the U.S. Department of Agriculture (USDA), the Food and Drug Administration (FDA), and the Environmental Protection Agency (EPA) cooperated in a nationwide study in which soil and crop samples collected from areas which had not received sludge were analyzed for heavy metal content (Wolnik et al. 1983). The range of concentrations found in soils from the southern U.S. is presented in Table 3.3 (U.S. Dept. Agr. et al. 1984). High concentrations of Cu in Florida may be attributed to extensive use of Cu fungicides. High Zn concentrations may be due to use of Zn on vegetables in Florida and on rice in Texas, Arkansas, and Louisiana.

Heavy metals are thought to exist in several forms in soil (Hodgson, 1963):

(1) in association with organic or inorganic surfaces;

(2) occluded during formation of a new solid phase;

(3) precipitated;

(4) in minerals as original component or through solid state diffusion;

(5) incorporated in biological systems and their residues.

TABLE 3.3

Heavy metal concentrations in soils[a] which have not received sewage sludge (U.S. Dept. Agr. et al. 1984)

State	Cd	Pb	Zn	Cu	Ni
	mg/kg				
AL	0.02-0.20	4-15	9-23	3.3-15.7	4.3-22.2
AR	0.06-0.37	11-25	25-120	8.5-34.5	8.9-35.7
FL	0.24-0.78	5-41	8-191	13.0-204	3.5-27.3
GA	0.02-0.13	3-24	2-50	1.1-19.6	2.2-29.7
LA	0.01-0.75	10-25	5-143	4.4-47.3	3.4-51.7
NC	0.05-0.19	7-20	5-33	4.0-27.1	2.8-26.7
OK	0.04-0.27	3-12	10-111	5.3-31.4	4.2-34.7
TX	0.03-0.50	2-25	4-115	1.8-29.6	2.5-33.6
VA	0.09-0.20	23-195[b]	49-95	12.4-60.1	15.1-34.3

[a]Soils digested in concentrated nitric acid
[b]Soils from apple orchards (use of lead arsenate)

Sposito et al. (1982) used a sequential extraction procedure similar to that of Stover et al. (1976) to estimate the forms of heavy metals in sludge-amended, alkaline soil in California. Zinc, Cd, and Pb were predominately in the carbonate form, Cu was mainly organically bound and Ni was predominately in the sulfide form. The forms of the metals will depend on soil properties, particularly pH, so Sposito's work is cited as an example of a method for determining metal forms in soils and not as information on possible metal forms in southern soils.

The main reaction of metals with soil organic matter (OM) is chelation. The metal ion enters an organic colloid by ion exchange and is then chelated, i.e., more than one bond forms between the metal and a molecule of the colloid with the formation of a heterocyclic ring which includes the metal ion (Leeper, 1970; Keeney and Wildung, 1977). Categorizing chelates by their solubility is helpful since solubility greatly affects their mobility and plant availability. If the chelate is a high molecular weight organic compound (eg., lignin) the chelate will be insoluble. Short-chain organic compounds form soluble chelates and thus promote movement of the metal. However, some short-chain compounds precipitate upon reaction with metals (Hodgson, 1963).

Metals may be adsorbed on the surface of hydrous oxides of Fe, Mn and Al (Leeper, 1970; Jenne, 1968; Ellis and Knezek, 1972; Fuller, 1978). These oxides exist both in crystal forms and as coatings on soil particles. The coatings are more active in metal reactions because of the higher surface area (up to 300 M^2/g). Surface adsorption and desorption of a particular metal is influenced by the concentration of the metal in solution, concentration of competing metals, pH and the dissolution and precipitation of the oxides themselves in response to variations in pH and Eh (Jenne, 1968).

Soil pH is an important factor in controlling heavy metal availability because it affects the retention of metals by organics and oxides and the extent of metal precipitation. Fortunately, pH adjustment is a relatively simple management tool for areas receiving sewage sludge.

Several laboratory, greenhouse, and field studies have been conducted in the South to determine the influence of soil properties on heavy metal availability. Heavy metal retention by the A and B horizons of 10 mineral soils from North Carolina was determined by equilibrating metal solutions with the soils for six days (L.D. King, unpublished data). Multiple regression analysis was used to determine which of 16 soil parameters was best related to the resulting nonexchangeable metal concentration in the soil. The best correlating soil property differed with the metals used (Table 3.4), but Fe oxides and pH predominated. In another study, the same soils were amended with lime or S to create a range of pH values and determine the effect of pH on Cd retention (L.D. King, unpublished data). Cadmium retention increased with increasing pH.

TABLE 3.4

Soil properties best correlated (multiple regressional analysis) with concentration of non-exchangeable metals in ten North Carolina soils. (L. D. King, unpublished data).

Metal	A horizon	B horizon
Cd	free Fe oxides[a]	organic matter
Ni	pH	pH
Cu	exchangeable K	pH
Zn	free Fe oxides	pH
Pb	amorphous Fe oxides[b]	free Fe oxides
Cr	organic matter and free Mn oxides[a]	clay content
Co	free Fe oxides	pH
Sb	(–) sand	(–) sand

[a]Sodium dithionite extractable
[b]Ammonium oxalate extractable

In the pH range 5.0-5.5, Cd retention was best correlated with free Fe oxides; but, from pH 6.0 to 7.0, retention was best correlated with free Al oxides or exchangeable Al.

Soil cation exchange capacity (CEC), along with pH, is used by regulatory agencies in setting allowable metal loading rates (Knezek and Miller, 1978) (also see Chapter 6). However, little evidence is available showing a good relationship between CEC and metal retention or availability. For example, in neither of the above studies with North Carolina soils was metal retention well correlated with CEC. In a greenhouse study Sims and Boswell (1976) added bentonite to a Cecil loam (Typic Hapludult) to increase the CEC and determine the resulting effect on metal extractability and uptake by wheat. Extractability and plant uptake were decreased by bentonite additions. However, since the bentonite was Ca saturated, soil pH was increased and it was not possible to separate the pH and CEC effects. In a Zn fertility study with 20 soils from the southern US, no significant correlation was found between corn ear-leaf Zn and CEC (Cox and Wear 1977). King (1981) found essentially no difference in uptake of sludge-applied metals by fescue from a Cecil (CEC 8.5 meq/100g) and a Norfolk soil (Typic Paleudult, CEC 3.9).

White and Chaney (1980) conducted a study to determine the relative importance of OM vs oxides of Mn and Fe in metal retention by soils. They compared the uptake of Zn and Cd by soybean seedlings from a Sassafras sandy loam (Typic Hapludult, OM 1.2%, CEC 5.4, dithionite Mn 281 mg/kg, dithionite Fe 3117 mg/kg) and a Pocomoke sandy loam (Typic Umbraqualt, OM 3.8%, CEC 16.0, dithionite Mn 1.3 mg/kg, dithionite Fe 557 mg/kg) from the Coastal Plain of Maryland. The Pocomoke was more effective than the Sassafras in reducing metal uptake, which indicates that OM was more effective than Fe and Mn oxides in retaining the metals.

In a greenhouse study with corn and soybeans, King and Dunlop (1982) applied sludge to a Norfolk loamy sand (1.4% OM) and three organic soils (19 to 72% OM). The pH of the Norfolk soil was adjusted to 6.5 as required by EPA's guidelines for sludge application (U.S. EPA, 1979). However, since the organic soils are normally maintained at pH 5.0-5.5 for crop production, lime was added to achieve this pH range (actual pH values ranged from 4.6 to 5.5). In the organic soils the high OM content offset the effect of the low pH so that metal uptake was similar in the organic and Norfolk soils.

Movement of Metals

An environmental concern of sludge use is the possible movement of sludge-applied metals through soil to groundwater or into surface water via runoff. In a greenhouse study Giordano and Mortvedt (1976) used columns of Ennis fine sandy loam (Fluventic Dystrochrept, pH 5.4) and Decatur silt loam (Rhodic Paleudult, pH 5.2) to determine the movement of sludge-applied metals. Sludge was mixed with soil in the upper part of the column at a rate to supply (in mg/kg of soil): Cd 4, Ni 23, Zn 168, Pb 128, and Cr 43. The treated soil was placed over a 45-cm-deep layer of untreated soil in the base of the columns. Periodic leaching over a 12-week period resulted in no metal leaching from the columns. Extraction of soil with 0.5*M* HCl showed little movement of metals from the treated to the untreated section of the columns.

In a 2-year field study, Boswell (1975) surface applied sludge to fescue on a Davidson clay loam (Rhodic Paleudult) to supply (in kg/ha) a total of: Cd 3, Cu 11, Zn 198, Pb 46 and Cr 30. Extraction of soil with 0.1*M* HCl showed little movement of metals below 30 cm. In a similar 2-year study on a Cecil clay loam, King and Morris (1972b) surface applied sludge to Coastal bermudagrass. The total quantity of Zn applied by the highest sludge rate was 612 kg/ha. At this rate no increase in exchangeable Zn was found below 30 cm.

Matthews et al. (1981) reported on a study in Alabama in which the quality of surface water draining from a watershed receiving sludge was compared with the quality of surface water from a control watershed. They found the NH_4^+, NO_2^- + NO_3^-, and total organic carbon concentrations increased due to sludge applications, but no increase in heavy metal concentrations was found. Results of a study in Tennessee showed that with a few exceptions, concentrations of heavy metals in runoff from a sludge-treated watershed were reasonably low and uniform throughout the sampling period. Relatively high metal concentrations were associated with high antecedent rainfall when the watershed had no vegetative cover (Shelton and Lessman, 1978).

Heavy Metals in Crops

Heavy metal concentrations in crops are affected not only by soil properties related to metal availability, but also by the physiology of the crop. For example, leafy crops like lettuce, chard and tobacco accumulate higher concentrations of metals than do crops like corn, soybeans, and forages. Also, metal uptake can vary considerably within a species. Hinesly et al. (1978, 1982) found that Cd concentration in corn grain varied by a factor of 4 between two hybrids and by a factor of 48 among 20 corn inbreds. In crops that produce seed or edible fruit, translocation of metals into the edible portion is generally low, with the result that the edible portion has a lower metal content than does the vegetative portion.

Background concentrations of heavy metals in several crops from areas in the South where sludge has not been applied are shown in Table 3.5. Notice that lettuce and spinach can have relatively high concentrations of Cd and Pb under natural conditions.

TABLE 3.5

Heavy metal concentrations in the edible portion of several crops grown in the southern US on soils which have not received sewage sludge (U.S. Dept. Agr. et al., 1984).

Crop	State	Metal[a]				
		Cd	Pb	Zn	Cu	Ni
		mg/kg				
Field corn	GA, NC	bdl-0.024	bdl-0.033	18-31	1.0- 4.1	bdl-0.3
Lettuce	FL	0.05-0.54	0.25 -1.20	50-88	3.5-11.0	no data
Onions	TX	0.03-0.12	0.032-0.078	8-23	3.1- 6.7	0.1-1.1
Peanuts	AL, GA, NC, OK, TX	0.03-0.19	0.001-0.045	24-43	5.1-13.5	0.4-8.1
Potatoes	AL, FL, NC, TX	0.08-0.51	0.013-0.59	8-29	2.0- 7.4	no data
Rice	AR, LA, TX	bdl-0.10	bdl-0.022	11-19	0.8- 3.7	bdl-0.4
Soybeans	AR, GA, LA, NC	0.01-0.16	0.006-0.128	37-69	4.0-25.0	0.9-14
Spinach	TX	0.67-1.25	1.0 -1.0	25-33	3.0- 9.9	0.2-1.9
Sweet corn	FL	bdl-0.23	0.010-0.064	28-46	1.9- 5.6	no data
Tomatoes	TX	0.09-0.19	0.022-0.066	17-26	3.8-13.0	0.2-1.4

[a]bdl = below detection limit

Greenhouse Studies

While the application of results of greenhouse studies to actual situations is limited, these studies help establish trends and provide information useful in setting up more definitive field studies. Mortvedt and Giordano (1976) showed that Zn from sludge is much less available than is Zn from $ZnSO_4$. They also found that two sludges with different Zn contents (1.4 and 0.2%), if applied at rates to supply equal rates of Zn, had similar effects on Zn concentrations in corn. King and Dunlop (1982) applied sludges with different Cd contents (Wilmington, N.C.: 13 mg/kg; Philadelphia, Pa.: 225 mg/kg) at rates supplying equal rates of Cd. In corn stover the rate of increase in Cd concentration with increasing loading rate was twice as great with the high Cd sludge as with the low Cd sludge. The difference in effect was thought to be due to the low Cd sludge supplying 13 times as much OM as did the high Cd sludge.

Sims and Boswell (1976) applied sludge from Atlanta, Ga. to wheat in a greenhouse study. Analysis of metals by plant part showed the concentration of Zn and Cd to be in the order root > leaves > stems > grain. The order of Cu and Ni was the same except that stems and grain were reversed. Sludge application rate had much more effect on Zn concentration than it did on the concentrations of other metals.

One practical aspect of sludge use that has received little attention is the effect of surface application vs incorporation on the availability of metals. Repeated applications of sludge to pasture or hay fields result in an accumulation of sludge solids at the soil surface (King and Morris 1973). The availability of metals in these solids is different from that of incorporated metals. King (1981) found that Cd, Ni, and Zn content of fescue was greater with surface-applied sludge than with incorporated sludge.

As previously mentioned, tobacco is known to be a Cd accumulator. During a 3-year period, samples of cured tobacco were collected from auction exchanges in Ontario and analyzed for a variety of metals and insecticides (Frank et al., 1977). Cadmium concentrations ranged from 1.25 to 7.02 mg/kg. Chaney (Sommers, 1980) reported that tobacco grown on soils with pH values ranging from 5.6 to 6.3 had Cd concentrations of 20 to 55 mg/kg in the lower leaves due to sludge applications supplying 0.8 to 4 kg Cd/ha. Hajjar (1985) conducted a greenhouse study in which tobacco and peanuts were grown in Wedowee loamy sand (Typic Hapludult) that had received sludge for 3 years in a field experiment. At pH 5.5, with no sludge additions, Cd content in the lower leaves was 2 mg/kg. With soil which has received 1.2 kg Cd/ha in the field study, Cd in the lower leaves was 40 mg/kg. Increasing the soil pH to 6.0 reduced the leaf concentration to 7 mg/kg, but a further pH increase to 6.5 did not reduce leaf Cd concentration further.

The effect of sludge on Cd in peanut tops was similar to the effect on Cd in tobacco. At pH 5.5 Cd increased from 1.6 mg/kg with no sludge additions to 12 mg/kg where sludge had supplied 1.2 kg Cd/ha. At pH 6 Cd in the tops was reduced to 2 mg/kg but increasing the pH to 6.5 did not further decrease Cd content. Soil pH had no significant effect on Cd concentration in peanut kernels. Cadmium in the kernels was increased from 0.25 mg/kg with no sludge to 0.36 mg/kg with sludge. Sludge had little effect on total plant yields when soil pH was above 6.0 but yields declined at pH 5.5. The decline was thought to be due to Zn toxicity since Zn concentration in the tops was 420 mg/kg.

TABLE 3.6

Results of field studies on the effect of municipal sludge on metal content of corn, soybeans, grain sorghum, and cotton.

State	Length of study	Soil	Sludge: Cumulative quantity	Sludge: Metal application rate Cd	Cu	Ni	Zn	Crop	Sludge[b]	Soil pH	Metal concentration in crop[a] Cd	Cu	Ni	Zn	References
	years		*mt/ha*	*kg/ha*							*mg/kg*				
FL	6	Orangeburg, Lucy, Troup fine sandy loams; Typic, Aeric and Grossarenic Paleudults, respectively	335	4	187	12	817	corn leaves	+	4.6	2.0	13	—	720	Lutrick et al., 1982; and Robertson et al., 1982.
									0	6.2	bdl	11	—	40	
								corn grain	+	4.6	bdl	3	—	100	
									0	6.2	bdl	3	—	20	
								sorghum leaves	+	4.6	bdl	11	—	240	
									0	6.2	bdl	8	—	40	
								sorghum grain	+	4.6	bdl	5	—	60	
									0	6.2	bdl	4	—	25	
								soybean leaves	+	4.6	0.8	12	—	600	
									0	6.2	bdl	8	—	70	
								soybean seed	+	4.6	bdl	14	—	150	
									0	6.2	bdl	10	—	40	
AL	3	Decatur silt loam Rhodic Paleudult	78	1.2	29	14	55	corn leaves	+	6.5	0.3	—	0.7	30	Giordano and Mays 1981, 1983
									0	6.5	0.2	—	0.7	13	
								corn grain	+	6.5	0.1	—	bdl	15	
									0	6.5	0.1	—	bdl	11	
								soybean petiole	+	6.5	0.4	—	6.8	42	
									0	6.5	0.5	—	3.2	29	
								soybean seed	+	6.5	0.3	—	6.2	38	
									0	6.5	0.3	—	4.5	33	
								cotton leaves	+	6.5	0.8	—	3.8	28	
									0	6.5	1.1	—	3.4	20	
								cotton seed	+	6.5	0.2	—	3.2	32	
									0	6.5	0.2	—	2.2	28	
GA	1	Cecil sandy clay loam Typic Hapludult	61	0.4	9	1	43	corn leaves	+	5.6	—	—	—	35	Sims and Boswell, 1980
									0	5.7	—	—	—	13	
								corn grain	+	5.6	—	—	—	27	
									0	5.7	—	—	—	18	
MD	1	Sassafras sandy loam Typic Hapludult	112	1.8	246	19	49	corn stover	+	6.2	1.0	10	1.7	286	Sheaffer et al., 1979 1979
									0	5.6	0.4	7	0.7	9	
								corn leaves	+	6.2	0.4	11	0.7	170	
									0	5.6	0.2	8	0.4	30	
								corn grain	+	6.2	0.1	2	1.6	41	
									0	5.6	0.05	1	0.3	18	
NC	3	Wedowee loamy sand Typic Hapludult	81	1.1	33	6	5	corn stover	+	5.0	0.3	6	bdl	99	King, unpublished
									0	6.6	bdl	4	bdl	23	
								corn grain	+	5.0	bdl	bdl	bdl	42	
									0	6.6	bdl	bdl	bdl	23	

[a]bdl = Below detection limit.

[b]+ = Sludge applied. 0 = No sludge.

TABLE 3.7

Results of field studies on the effect of municipal sludge on metal content of forage crops.

			Sludge								Metal concentration in crop[a]				
				Metal application rate											
State	Length of study	Soil	Cumulative quantity	Cd	Cu	Ni	Zn	Crop	Sludge[b]	Soil pH	Cd	Cu	Ni	Zn	References
	years		*mt/ha*	------------ *kg/ha* ------------							------------ *mg/kg* ------------				
GA	2	Davidson clay loam	17	3	11	—	198	fescuegrass	+	6.2	28	117	—	1420	Boswell, 1975
		Rhodic Paleudult							0	6.2	2	10	—	25	
NC	1	Braddock loam	21	1.8	10	2.6	32	fescuegrass	+	5.5	1.1	9	bdl	45	King, unpublished
		Typic Hapludult							0	5.5	0.5	6	bdl	30	
GA	2	Cecil sandy clay loam	137	—	64	4	342	coastal	+	5.1	—	8	—	160	King and Morris,
		Typic Hapludult						bermudagrass	0	5.2	—	7	—	20	1972a, 1972b, 1973
								rye (overseeded	+	4.7	—	12	—	232	
								in coastal bermuda)	+	limed	—	11	—	186	
									0	4.8	—	10	—	31	
GA	5	Cecil sandy clay loam	137	—	64	4	342	coastal	+	5.5	bdl	6	—	153	Touchton et al., 1976
		Typic Hapludult						bermudagrass	+	5.8	bdl	—	—	92	
									0	5.4	bdl	7	—	19	
MD	1	Sassafras sandy loam	112	1.8	246	19	493	arrowleaf clover	+	6.2	0.4	14	11	312	Sheaffer et al., 1979
		Typic Hapludult							0	5.6	0.1	7	2	51	
								crimson clover	+	6.2	0.05	9	4	112	
									0	5.6	0.04	7	1	50	
								oats	+	6.2	0.2	3	7	42	
									0	5.6	0.1	2	1	13	
								rye	+	6.2	0.2	7	2	94	
									0	5.6	0.1	4	0.4	21	
								wheat	+	6.2	0.2	4	2	72	
									0	5.6	0.02	2	0.4	19	

[a]bdl = Below detection limit.

[b]+ = Sludge applied. 0 = No sludge.

Field Studies with Row Crops

Results of several field studies with row crops are summarized in Table 3.6 and are discussed below. Sludge from Pensacola, Fla. was applied to a fine sandy loam soil over a 6-year period at cumulative rates up to 335 mt/ha. This high rate greatly depressed soil pH and significantly increased Cd content in corn and soybean leaves. Copper was affected slightly, but Zn was dramatically increased by sludge additions. Soybean yields declined with increasing sludge rate and the decline was thought to be due to Zn and Mn toxicity. The investigators concluded that an annual sludge rate of 28 mt/ha would be acceptable.

Application of sludge at 78 mt/ha to a silt loam soil in Alabama resulted in little effect on Cd content of corn, soybeans or cotton. Sludge increased Ni concentrations, particularly in soybean petioles. Zinc was increased slightly in all crops. Applications of a low metal sludge to a clay loam soil in Georgia resulted in small increases in Zn in corn. However, in a study in Maryland, application of a sludge with a high metal content resulted in increased metal concentrations in corn. The most dramatic increase was in Zn concentration. In a North Carolina study, concentrations of Cd, Cu and Zn in corn stover were increased by sludge additions but only Zn concentration was increased in the grain.

Field Studies With Forage Crops

Results of several field studies with forages are summarized in Table 3.7 and are discussed below. Application of sludge from Atlanta, Ga. to an established fescue sod resulted in high concentrations of metals in the harvested grass. The grass samples were washed in distilled water after they were harvested but since they were not acid washed and since fescue has a rough surface, the high metal values probably resulted from sludge surface contamination. Sludge from Asheville, N.C. was applied to fescue plots which had been closely mowed prior to sludge application. Metal concentrations were increased by sludge applications, but due to lack of contamination, increases were smaller than in the Georgia study. Chaney and Lloyd (1979) reported that when sludge was spray-applied to fescue, sludge adhering to fescue accounted for 22 to 32% of the weight of the grass (+ sludge) on the day of application. The sludge could not be removed by washing with a detergent. King (1982) also reported significant contamination of fescue hay which had received untreated industrial waste water via spray irrigation. The above cases show that even though plant uptake of Pb and Cr is very low, grazing animals could ingest these metals from contaminated forage. They also stress the need for close grazing or mowing prior to sludge application.

Sludge from Athens, Ga. applied to Coastal bermudagrass increased Cu and Zn concentrations in the grass. The sludge also increased heavy metal concentrations in rye that was overseeded in the bermudagrass in the fall. Liming reduced the heavy metal effects of the sludge. The study was continued 3 years after the last sludge application to determine the residual effect of sludge. Zinc concentrations were still elevated but liming reduced the effect of sludge on Zn in plant tissue.

Studies in Maryland showed the effect of sludge on metal content of clovers and small grain forages. Cadmium and Cu were increased slightly but increases in Ni and Zn were more pronounced.

Vegetable and Fruit Crops

The potential human health hazard posed by application of Cd via sludge to forage or row crops used for animal feed is minimal because of the "animal filter" discussed previously. However, the potential is greater with vegetables and fruits consumed directly. Giordano et al. (1975) determined the effect of a single application and two annual applications of sludge on metal content of sweet corn and bush beans (Table 3.8). Cadmium in corn grain was doubled or tripled but Ni and Zn were not as dramatically affected. At the end of 2 years, little or no difference was found in the effect of a single sludge application or two annual applications on metal concentrations. Sludge additions had little effect on Cd concentrations in bean pods but Ni and Zn were increased, particularly the second year. Annual applications resulted in higher Zn concentrations than did the single application but Cd and Ni generally were not affected by the number of applications.

In a later study Giordano et al. (1979) determined the effect of a single 224 mt/ha application of sludge from Decatur, Ala. on the Zn and Cd content of a variety of

TABLE 3.8

Metal concentrations in sweet corn and bush beans growing on a Sango silt loam (Glossic Fragiudult, pH 5.4) amended with 50 mt/ha of sludge from Tuscumbia, AL (supplying 2.5 kg/ha Cd, 14 kg/ha Ni and 90 kg/ha Zn per application) (Giordano et al., 1975)

Crop	Year	Sludge[a]	Cd	Ni	Zn
			mg/kg		
Corn grain	1	+	0.9	4.0	43
		0	0.3	5.1	37
	2	+ +	0.7	1.1	50
		+	0.7	0.8	47
		0	0.4	1.0	35
Bean pods	1	+	0.2	6.9	61
		0	0.2	5.0	45
	2	+ +	0.2	8.8	96
		+	0.2	9.2	72
		0	0.1	4.5	49

[a] 0 = no sludge applied
\+ = sludge applied the first year only
\+ + = sludge applied both years

garden crops (Table 3.9). As expected, the sludge addition greatly increased Cd concentration in lettuce (by 54 to 350%) and the effect persisted through the third year. Zinc concentration in lettuce was also increased (by 54 to 300%), but not as dramatically as was Cd concentration. Liming reduced the effect of sludge on both metals. For the other crops, the maximum increase in Zn due to sludge was 60%. Sludge did not significantly increase the Cd in potatoes, but in the other crops Cd increases ranged from 19% (cabbage, limed soil) to 1830% (corn). Where sludge was applied, liming had little effect on the Zn concentrations in pepper, cabbage, carrots, and cantaloupe or on the Cd content of peppers. Liming did reduce Cd in the cabbage, carrots, and cantaloupe.

Conclusions

Plant availability of Pb and Cr is low, but introduction into the food chain can occur by direct ingestion of sludge by grazing animals. Cadmium is the heavy metal that may pose a health problem since plant concentrations can increase to levels that would be toxic to consumers but not to the plant itself. However, soil adsorption and partitioning in plants and animals work to prevent large increases in Cd in the human food chain due to sludge additions.

Heavy metals are held in the soil in a variety of forms and their availability is affected by those forms. In mineral soils, pH is probably the most important factor controlling availability. Field and laboratory studies have shown little metal movement in soils.

Sludges are higher in Zn than in other metals (Table 3.1) and results of the above field studies (Tables 3.6 and 3.7) and greenhouse studies show that sludge applications have their greatest impact on Zn content of crops, particularly when soil pH is low (sometimes depressed by the sludge additions). Copper concentrations are not greatly affected, as evidenced in the Maryland study (Table 3.6) in which a high rate of Cu was applied but increases in Cu in the crops were generally small. In contrast, Ni and Cd can affect plant content even when these metals are applied at relatively low rates. In the studies on vegetables (Table 3.9), with the exception of lettuce, sludge did not affect Zn concentration to the extent that it did in field crops.

As expected, sludge applications resulted in plant metal concentrations that were higher than the background concentrations found in the USDA study (Table 3.5). However, in the various sludge experiments reported here, the metal concentrations in crops in the control treatments (i.e., receiving no sludge) were generally higher than the range reported in the USDA study.

TABLE 3.9

Cadmium and Zn concentrations in edible portions of crops grown on a Sango silt loam (Glossic Fragiudult) amended with a single application of 224 mt/ha of sludge from Decatur, AL (supplying 11 kg/ha Cd and 400 kg/ha Zn) (Giordano et al., 1979).

						Year 3					
		Year 1		Year 2		No Lime			Lime		
Crop	Sludge[a]	Zn	Cd	Zn	Cd	Zn	Cd	pH[b]	Zn	Cd	pH[b]
		mg/kg									
Lettuce	+	74	3.56	131	10.4	116	3.10	6.0	63	1.85	6.7
	0	48	0.86	54	0.30	29	0.95	4.6	31	0.90	6.3
Broccoli	+	99	0.89	—	—	—	—		—		
	0	87	0.27	—	—	—	—		—	—	
Eggplant	+	22	1.64	—	—	—	—		—	—	
	0	15	0.54	—	—	—	—		—	—	
Tomato	+	40	1.04	—	—	—	—		—	—	
	0	26	0.52	—	—	—	—		—	—	
Potato	+	19	0.10	—	—	—	—		—	—	
	0	16	0.11	—	—	—	—		—	—	
Corn	+	—	—	40	1.83	—	—		—	—	
	0	—	—	25	0.10	—	—		—	—	
Squash	+	—	—	21	0.27	—	—		—	—	
	0	—	—	19	0.15	—	—		—	—	
Pepper	+	—	—	45	1.30	33	0.97		29	0.98	
	0	—	—	36	0.25	29	0.24		24	0.19	
Bean	+	—	—	73	0.21	—	—		—	—	
	0	—	—	64	0.07	—	—		—	—	
Cabbage	+	—	—	—	—	59	0.35		46	0.19	
	0	—	—	—	—	48	0.19		29	0.16	
Carrot	+	—	—	—	—	30	2.29		29	1.25	
	0	—	—	—	—	39	0.96		22	0.71	
Cantaloupe	+	—	—	—	—	25	0.82		20	0.44	
	0	—	—	—	—	18	0.21		18	0.21	

[a]0 = no sludge
+ = sludge

[b]pH levels apply to all crops.

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Chapter 4

Considerations for the Application of Salt-containing Wastes to Agricultural Lands

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The concentration and composition of salts contained in waste materials may limit the amount of wastes that can be applied to land areas without seriously degrading the soils and reducing yields and quality of subsequent crops. Previous research has defined some limits in terms of soil and crop factors and the nature of the salts involved (Bernstein, 1964, Richards, 1954). Application of the information to areas other than the arid soils of western U.S. has been satisfactory if rainfall, soil, and drainage are considered.

Salts added in wastes, such as manures and sewage sludges, can be handled best by monitoring total salts applied and build up of salts in the soil profile with rate of application and time. Prevention of salt problems is an easier and safer approach than risking the need for soil reclamation.

Limitations of Salt Application by Sludges

Plants differ in their sensitivity and productivity with salt in their growth medium. Application of sludges to soils containing salts should be limited to avoid serious reduction in yields of crops.

Proper management of soils in regard to salts requires periodic measurement of salt application rates and accumulation in soil by depth. Standard analytical procedures for determining salt composition and total salts are usually employed for sludges. The total concentration of ions usually has more affect on growth of plants than does the composition of ions. Thus, for most purposes, soil salinity can be determined satisfactorily by saturating a soil sample with distilled water, extracting the water from the sample and measuring the electrical conductivity (Ec) of the extracted solution. The salt concentration can then be estimated from this Ec, i.e., salt concentration (mg/L) $\approx$ 640 x Ec (millimhos/cm) The relationship of Ec to relative productivity of several crops is shown in Table 4.1 (Bernstein, 1964).

Special attention is directed to the sodium (Na) percentage and/or the Na adsorption ratio (SAR) because of the changes they can cause in soil characteristics that affect soil management and plant growth. When Na salts are added to a soil to the extent that approximately 12-15% of the CEC is occupied by Na, the structure of medium and fine textured soils begins to deteriorate. Permeability to air and water decreases markedly, the extent depending on texture, clay mineralogy, and total salt and sodium ratios. Sodium "toxicity" may also become a factor for Na sensitive crops; i.e., some beans are adversely affected when the exchangeable Na percentage approaches 10%.

TABLE 4.1

Soil salt content (measured by electrical conductivity [Ec]) associated with reductions in crop growth (Bernstein, 1964).

	Reductions in crop growth		
	10%	25%	50%
	Ec, millimhos/cm at 25° C		
Bermudagrass	13	16	18
Barley	12	16	18
Tall wheatgrass	11	15	18
Sugar beets	10	13	16
Cotton	10	12	16
Tall fescue	7	11	15
Wheat	7	10	14
Sorghum	6	9	12
Soybean	6	7	9
Paddy rice	5	6	8
Corn	5	6	7
Alfalfa	3	5	8
Orchardgrass	3	5	8
Red clover	2	3	4

Gypsum ($CaSO_4 \cdot 2H_2O$) can be applied to fields receiving Na to prevent a Na buildup or displace Na already adsorbed on the CEC. The quantity of pure $CaSO_4 \cdot 2H_2O$ required to supply Ca equivalent to the amount of adsorbed Na can be calculated from the following equation:

Gypsum, kg/ha = 12.9 x CEC x ESP x BD where:
CEC is in meq per 100 g soil
ESP (exchangeable Na percentage) is in percent
BD (bulk density) is in g/cm³.

The equation calculates the quantity required for a soil depth of 15 cm. Replacement of Na by Ca will not be 100% so an efficiency factor of 50% should be used and for fine textured soils 25% should be used.

Gypsum should be used in a regular maintenance program because preventing Na buildup is much easier than correcting a problem after the fact.

Disposal of Other Wastes with High Na Contents

Oil well drilling fluid disposal by land application (land farming) is being proposed in some of the southern states. Several potential problems are envisioned. Barite ($BaSO_4$), used to increase drilling fluid density for deeper wells, will have increased solubility in acid soils, and may be a problem requiring investigation. Common impurities of natural barite include CaF_2, Pb, As, Zn, Cd, Hg, and Cu (Gray and Darley, 1980) some of which could be toxic to plants and/or plant consuming animals. In addition, Cr is included in drilling fluids for rust inhibition and as Cr-lignosulfonate, an extender. Care in addition of the above elements must be exercised, and research work is suggested for definition of danger or limits.

The most likely problem encountered with disposal of waste oil well drilling fluids is the high content of Na. Though drilling fluids often contain in excess of 50,000 mg/L salt (most often NaCl), 30 to 20,000 mg/L will be encountered more frequently. If fluids containing 20,000 mg/L NaCl are considered, 31,500 kg gypsum ($CaSO_4 \cdot 2H_2O$) per ha cm of waste fluid would be required for reduction of SAR to a minimum of 8. If the desired SAR were 4, then 127,500 kg would be required.[1]

If corrections for a fluid density above 1 and an efficiency factor are assumed, i.e. if fluid density = 2 and an efficiency factor of 50% are used, weight of gypsum will be 4 times the above values.

Ratio for minimum recommended rates of application of waste fluids to soil (by weight) is 1:4, prescribed to be mixed into a 15-cm layer of soil. In this case, with the assumed density of 2 and allowing an efficiency factor of 50%, the amount of gypsum required to correct a 20,000 mg/L NaCl fluid to SAR = 8 is 480,000 kg.

We propose that the SAR correction approach may not apply for a situation of this nature, but that an equivalent replacement of Na^+ be calculated and an efficiency factor assumed. If the efficiency factor assumed is 50%, 4500 kg of gypsum must be applied per 1.5 ha cm of waste drilling fluid containing 20,000 mg/L NaCl, by weight, and the fluid having a density of 2. If the efficiency factor is 25%, then 9000 kg of gypsum would be required. The question as to whether this approach is satisfactory will depend upon quality of leaching water, soil mineralogy, and soil drainage. Research in this area is needed, in relation to suitable application methods as much as any other aspect, since moisture acceptance and infiltration rates will be critical in most cases.

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[1]Calculations are made presuming (Mg^{++}) negligible or equivalent correction is made to (Ca^{++}): with this simplification:

$$(Ca^{++}) = \frac{2(Na^+)^2}{(SAR)^2}$$

where (Na^+) and (Ca^{++}) concentrations are in meq/L, the fluid density assumed to be =1, and Ca^{++} of the mud itself not entering into the determination.

Chapter 5

Management

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Management is the logical sequencing of those activities needed to operate the system as designed—based on available information and experience. The overall system cannot function properly without management, regardless of the amount and quality of sludge and the proper design of system components for land application. This chapter discusses many of the factors that must be considered when developing a management plan for a sludge application system.

Sludge Storage

Sludge must be stored periodically depending on weather and soil conditions, available land, and the goals of the land application system.

The storage volume required depends on several factors:

1. Type of wastewater to be treated (municipal or industrial) and size of treatment plant;
2. Method of treatment (primary, trickling filter, activated sludge, etc.);
3. Method of sludge stabilization (aerobic, anaerobic, lime, heat or composting);
4. Moisture content of sludge (heat drying, drying beds, filters, etc.);
5. Cropping practice and time available between cropping seasons for land application;
6. Effect of soil moisture conditions on trafficability and potential for runoff water.

The designer must have information available on the above items to accurately estimate the required volume of the sludge storage structure. For example, under item 2 above, an activated sludge system may produce 25 times more sludge than a trickling filter, 20 L/m^3 vs. 0.7 L/m^3. Sludge from primary sedimentation will be approximately 3 L/m^3 (U.S. Environ. Protection Agency, 1974). In designs for six different treatment plants the expected sludge production ranged from 3 to 10 L/m^3 of wastewater to be treated (Smith, et al., 1982).

If sludge is concentrated (e.g. by settling or filtering) the solids content will increase from 2-3% to as much as 8-12% with a resulting decrease in the sludge volume.

Knowledge of cropping practices is important to determine the availability of land for sludge application. For example, if corn is grown on the entire site, sludge will have to be stored 100 days for silage corn and longer for grain production. Where pasture or hay land is also available, sludge could be applied to these areas when application is not practical on crops such as corn or small grain. If sludge is being applied to several farms, the variety in the cropping practices may be such that suitable land will be available for longer periods. Generally, the largest quantity of available land will occur in the spring and fall when there are no growing row crops.

Climatic conditions may have more influence than the cropping practice on the storage requirements. Sludges should not be applied during extended periods of wet weather due to soil compaction problems and the pollution potential from runoff water. Several EPA programs (Loehr, et. al., 1979) are available to estimate the storage requirements for wastewater application based on climatic conditions only. These programs may also be helpful in estimating sludge storage requirements. The National Climatic Center at Asheville, N.C. has long term weather data for all reporting stations in the U.S. In the midwestern and northern states the successive days of freezing weather will be the controlling factor, while in the southeastern states successive days of wet weather will be the controlling factor. The EPA program (weather data from 1950-1972) estimates the days of storage required based on soil conditions being too wet if wastewater was applied with resulting runoff problems. The range in storage days for some of the states in the Southeast are: AL, 13-24; FL, 8-16; GA, 10-17; LA, 11-35; MS, 12-33 NC, 11-14; and SC, 9-24 (Loehr, et. al., 1979). The lower part of the above ranges would be for cities that have lower rainfalls and less permeable soils than those cities in the higher ranges. Design of sludge storage lagoons for several muncipalities in the Midwest resulted in storage times from 20 to 400 days (Smith, et al., 1982). Recommendations from Ohio suggest a 30 day storage time (Miller, et al., 1979).

Stabilized sludge will not change significantly during storage if the storage is relatively short term (less than 30 days). Many of the relatively easily degradable organics have been destroyed during the stabilization procedure so chemically and biologically the sludge is quite stable. Pathogenic organisms are also reduced. Some form of agitation in the sludge storage structure is recommended to get the settled solids back into suspension prior to pumping. For very large sludge storage structures, providing sufficient agitation is difficult because of a lack of adequate equipment. Extensive descriptions of facultative, anaerobic and aerobic sludge lagoons are available (U.S. Environ. Protection Agency, 1979).

Sludge storage structures are usually earthen or fabricated. The earthen type is generally used for the large, long term storage requirements. It is the least expensive based on a cost per volume of storage. If the soil is relatively fine textured and the bottom of the excavated lagoon is above the groundwater table, the chance of seepage will be minimal. A layer of clay in the bottom of the excavated lagoon is recommended to reduce the chance of seepage. Typical depths will be from 2 to 6 m. If the soil is highly permeable or only short term storage is required, an above ground or below ground concrete or metal tank is suitable. Unused digesters or tanks at the treatment plant would be suitable for temporary sludge storage.

Transportation

Sludges are frequently generated some distance from the ultimate application site. Depending on the solids content of the sludge, various handling methods can be utilized (Table 5.1).

Based on sludge characteristics, transport distances, quantities of sludge to be transported, and other pertinent considerations various transport modes may be selected. Table 5.2 identifies transport modes that are mostly frequently utilized.

TABLE 5.1

Sludge solids content and handling methods (Knezek and Miller, 1978).

Sludge type	Solids content	Handling methods
	%	
Liquid	1-10	Gravity flow, pump, tank transport
Semisolid (wet solids)	8-30	Conveyor, auger, truck transport
Solid	25-80	Conveyor, bucket, truck transport

TABLE 5.2

Transport modes for sludges (Knezek and Miller, 1978).

Transport type	Sludge type	Characteristics
Rail tank car	Liquid	90 wet metric tons (90 m^3) capacity; suspended solids will settle while in transit.
Barge	Liquid	Capacity determined by waterway; Chicago has used 1100 wet metric tons (1100 m^3) barges.
Pipeline	Liquid	Need minimum velocity of 0.3 mps to keep solids in suspension; friction decreases as pipe diameter increases (to the fifth power); buried pipeline suitable for year round use.
Tank truck	Liquid	Capacity, up to maximum load allowed on road. Can have gravity or pressurized discharge. Field trafficability can be improved by using flotation tires.
Farm tank wagon & tractor	Liquid & semisolid	Capacity, 3 to 11 m^3. Principal use would be for field application.
Rail hopper car	Solid	Need special unloading site and equipment for field application.
Truck	Solid	Commercial equipment available to unload and spread on ground; need to level sludge piles if dump truck is used.

Several reports describe the virtues of the many transport modes that can be utilized in determining appropriate options for specific conditions. Ettlich (1977) has compared the relative costs of transport modes based on amounts of sludge to be hauled and estimated hauling distance. An EPA Process Design Manual (U.S. Environ. Protection, Agency, 1979) devotes an entire chapter to engineering data and methodology to enable sizing equipment for specific situations. Numerous case studies and state guidelines can provide valuable input on transport techniques (Manson and Merritt, 1975; White et al., 1980a, 1980b; Goldstein, 1981; White and Brown, 1981; White, et al., 1982).

Application

As previously discussed, the scheduling of sludge application is dependent upon weather, soil conditions and cropping schemes. In the southeast periods of high rainfall will prevent sludge application. Certain soil types may also limit land application. On the other hand, relatively short periods of freezing weather can be expected. Another major consideration is the method of sludge application. The application method will depend on sludge solids content and the objectives of sludge utilization—odor control, nutrient utilization, etc. Solid or semisolid sludge is typically broadcast on sod or "open" land. It may or may not be incorporated. Liquid sludge can be irrigated, broadcast, broadcast and incorporated, or directly injected below the soil surface.

Variations are possible in the methods of application. For example, liquid sludge can be irrigated using solid set, travelling gun, or center pivot equipment. It can also be accomplished on level land using overland flow, flooding, or ridge-and-furrow irrigation, although it may be difficult to achieve acceptably low loading rates with these methods. Sludge may be injected with an injector-fitted spreader truck or pumped to the field through solid line, into the field using flexible line, and applied by a crawler tractor pulling a specially designed injector.

Major considerations for selecting application equipment include:

1. Solids content of sludge
2. Slope on receiving site
3. Need or desire for direct incorporation
4. Quantity of sludge to apply.
5. Soil and weather conditions compared to sludge storage volume.
6. Transport system to application site
7. Rate of application needed
8. Odor potential
9. Runoff potential

The application method affects time of application. Irrigation of liquid sludge may occur before, during, or after crop production. Broadcast or direct incorporation of liquid sludge typically is limited to before or after crop production. The exception being application to sod crops. However, the city of Raleigh, N.C. has found that liquid sludge can be broadcast via tank trucks with high flotation tires on small grains and even corn in the seedling stage without permanent damage to the crop.

Tables 5.3 and 5.4 describe the available equipment for liquid, semisolid and solid sludges. Additional references containing useful information include Torrey, 1979; U.S. Environ. Protection Agency, 1979; White et al., 1982; Smith, et al., 1982.

Cropping Systems

Sludge application practices will vary depending on the crops being grown, cropping sequences, sludge stabilization method, and nutrient availability.

Grasslands

Grasslands used for grazing, hay or ground cover offer considerable flexibility in time of sludge application because the soil has year-round cover and can usually support vehicular traffic on all but the very wettest days. However, sludge injection is more difficult with sod crops, particularly if one is concerned about damage to the sod by injector shanks. While surface application is agronomically acceptable, odors may be a constraint if the application site is near occupied areas. Also, ammonia losses may be significant with surface application.

In a review article, Chaney (1982), reported that sludges adhere to forages and row crops in significant amounts if applied when top growth is present. However, if forage is cut or heavily grazed just prior to sludge application and grazing is then delayed for several weeks, animals consume the new growth (or it is cut for hay) and sludge ingestion is minimized. Since cattle ingest soil as part of the normal grazing process (Chaney, 1982), sludges high in heavy metals and/or toxic organics (e.g. PCBs) should not be surface-applied to pastures.

The amount of sludge which can be efficiently utilized on grasslands depends on N availability and to a great extent on the species or mixtures of species present. Leguminous forages do not require fertilizer N and will receive the least economic benefit from sludge application. Sludge will meet all the P but very little of the K requirements of legumes. Sludge N may be detrimental in that it can result in excessive competition from weedy grasses.

Bermudagrasses, both common and the various forage hybrids, are the highest yielding grasses grown in most of the South. Yields can be as high as 18 to 27 dry metric tons/ha depending on geographical area. Nitrogen uptake by bermudagrass at these yield levels ranges from 300 to 500 kg/ha. Thus, bermudagrass can utilize heavy applications of sludge. However, since the efficiency of N uptake by the grass decreases with increasing rate of sludge application, high sludge application rates may lead to pollution of ground water by nitrate.

Cool season grasses such as tall fescue and orchard grass as well as bahiagrass and some of the range grasses grown in the Southwest are not nearly as high yielding as bermudagrass and can efficiently utilize a maximum of about 200 kg/ha of available N. In the South, cool season grasses suffer stress in the summer and this stress is aggravated if soil fertility is high. Since nutrients in sludges are released slowly, release of nutrients from spring-applied sludge may continue into the summer and result in high concentration of nutrients in the soil. Stand damage has been observed where high rates of manure and manure lagoon effluent (Westerman et al., 1983), industrial wastewater and sludge (R. Cutchin, unpublished data), and municipal sludge (L.D. King, unpublished data) have been applied to fescue. Therefore, sludge should be applied at

TABLE 5.3

Application methods and equipment for liquid and some semisolid sludges (Knezek and Miller, 1978).

Method	Characteristics	Topographical and seasonal suitability
Surface application		
Irrigation spray (sprinkler)	Large orifice nozzle required; large power and lower labor requirement; wide selection of commercial equipment available; sludge must be flushed from pipes when irrigation completed.	Can be used on sloping land; can be used year-round if the pipe drained in winter; not suitable for application to some crops during growing season; odor (aerosol) nuisance may occur.
Ridge and furrow	Land preparation needed; lower power requirements than spray.	Between 0.5 and 1.5% slope depending upon percent solids; can be used between rows of crops.
Overland flow	Used on sloping ground with vegetation with no runoff permitted; suitable for emergency operation; difficult to get uniform area application.	Can be applied from ridge roads.
Tank truck	Capacity 2 or more than 8 m^3; larger volume trucks will require flotation tires; can use with temporary irrigation set-up; with pump discharge can spray from roadway onto field.	Tillable land; not usable with row crops or on soft ground.
Farm tank wagon and tractor	Capacity, 2 to 11 m^3; larger volume will require flotation tires; can use with temporary irrigation set-up; with pump discharge can spray from roadway onto field.	Tillable land; not usable with row crops or on soft ground.
Subsurface application		
Flexible irrigation hose with plow furrow or disc cover	Use with pipeline or tank truck with pressure discharge; hose connected to manifold discharge on plow or disc.	Tillable land; not usable on wet or frozen ground; reduce runoff and odor potential.
Tank truck with plow furrow cover	2 m^3 commercial equipment available; sludge discharged in furrow ahead of plow mounted on rear of 4-wheel drive truck.	Tillable land; not usable on wet or frozen ground; reduce runoff and odor potential.
Tank truck with injection knives	6 to 19 m^3 commercial equipment available.	Tillable land; not usable on wet or frozen ground; reduce runoff and odor potential.
Farm tank wagon and tractor:		
Plow furrow cover	Sludge discharged into furrow ahead of plow mounted on tank trailer (application of 380 to 500 wet metric tons/ha); or sludge spread in narrow band on ground surface and immediately plowed under (application of 100 to 280 wet metric tons/ha).	Tillable land; not usable on wet or frozen ground; reduce runoff and odor potential.
Subsurface injection	Sludge discharged into channel opened by a tillage tool mounted on tank trailer (application rate 60 to 120 wet metric tons/ha); vehicles should not traverse injected area for several days.	Tillable land; not usable on wet or frozen ground; reduce odor and runoff potential.

TABLE 5.4

Methods and equipment for application of semisolid and solid sludges (Knezek and Miller, 1978).

Method	Equipment
Spreading	Truck-mounted or tractor powered box spreader (commercially available); sludge spread evenly on ground; application rate controlled by over-the-ground speed; can be incorporated by discing or plowing.
Piles or windrows	Normally hauled by dump truck; spreading and leveling by bulldozer or grader needed to give uniform application; 10- to 15-cm layer can be incorporated by plowing.
Reslurry and handle as a liquid (as in Table 5.3)	Suitable for long hauls by rail transportation.

agronomic rates to cool season grasses in the fall so that by the following summer, most of the available nutrients will have been utilized by the grass.

Row Crops

The row crops most likely to be grown on sludge amended lands include corn, cotton, soybeans, and sorghum. Sugarbeets, white potatoes, and sweet potatoes can also be classified as row crops but are less suitable for growing with sludge since the harvested portion of the plant is in direct contact with the soil. Grain or seed crops are lower in heavy metals (especially Cd) because the metals are partially excluded from grain or seed portion of the plant.

Corn and grain or silage sorghums appear to be the most desirable row crops to grow on sludge-amended land because of their high nutrient requirement. Corn grown for grain can utilize from 170 to 220 kg/ha of available N per year and large amounts of P and K. Nutrient requirements are two-thirds as great for sorghum as for corn but there is the same need for a balanced supply of nutrients as with corn. When corn or sorghum is harvested for silage, the nutrient requirements are higher because of the nutrients removed in the stalks.

Inability to apply sludge during the growing season is the chief constraint to the use of row crop land for sludge application. Some land must be held out of production each year to have continuous application sites. An alternative is to provide a sufficient acreage of grassland for sludge application during the row crop season. During crop surplus periods when the federal government uses some form of acreage reserve to control farm production, use of diverted acres for sludge application may be possible. While this situation allows for sludge application during the growing season with a minimum of lost income, such opportunities cannot be expected to exist every year. Also if no crop is removed from the diverted area then N will accumulate and could pose a ground water pollution hazard.

Small Grains

Small grains are another crop for lands fertilized with sewage sludge. Types grown in the South are usually planted in October and harvested from mid-May to late-June depending on variety and location. Wheat and barley are often grown in double cropping systems with soybeans or grain sorghum. Rye may be planted for winter grazing or as a winter cover crop and is not harvested for grain but may be followed by a row crop or a summer annual grazing crop.

Sludge can be injected or surface applied in the fall before planting or in the early summer after harvest of wheat or barley.

In addition, it can be surface applied on the growing crop throughout the late fall and early winter period where grazing is not practiced. Spring application from the time stem elongation starts until harvest will damage the crop and should be avoided.

The N requirement is much lower for small grains than for corn and some of the high yielding forage grasses. Excessive N application on wheat or barley may cause severe lodging and crop loss.

Nutrient Requirements of Crops

Nutrient requirements of crops vary widely depending on the plant species and the way the crop is used. With forage crops, the requirement is higher for hay than for pasture, partly because more of the plant nutrients are returned to the soil in urine and feces or in unused plant material. A corn crop harvested as silage removes about twice as much N, P, and K as a crop in which only the grain is removed.

Sludge application rates should be based on soil tests and the fertilizer recommendations which have been developed in each state. Since the P/N ratio in sludge is much higher than that required by crops, sludge rates supplying adequate N will oversupply P. To make more efficient use of nutrients in sludge, sludge can be applied to supply the P requirements of the crop and supplemental N fertilizer added.

Vegetable Crops

While some vegetables can be safely grown on sludge-amended soils, numerous restraints should be considered. Root crops such as onions and carrots, etc., which are often consumed raw, may become contaminated with pathogens if grown within two years after sludge application. Also Chaney (1982) has discussed the hazards from toxic organic compounds which may be applied to the land in industrial sludges.

Sludges containing Cd can cause unsafe Cd levels in the edible portions of numerous vegetable crops. Bingham et al. (1975, 1976) and Giordano et al. (1979) measured heavy metal uptakes by numerous food crops. Among those accumulating the most Cd were lettuce, turnips, carrots, and beets. These potential problems can be avoided by not applying sludge to most vegetable producing land. Tobacco is another crop which should be excluded from land treated with sludge as it is also a heavy accumulator of Cd.

Use in Land Reclamation

Sewage sludge is particularly useful in the reclamation of surface-mined areas, sand tailings piles, borrow pits, and other disturbed land areas. These sites are devoid of organic matter, very low in N, possibly low in pH and in P and K, and have poor physical structure. Almost any non-toxic material which adds organic matter and plant nutrients will have beneficial effects on such sites.

Since disturbed sites often have only limited usefulness for crop production, some areas might be used as dedicated sites for sludge application. However, since the soil strata may have been disturbed for many feet below the surface and initial vegetative cover may be quite low, the potential for groundwater pollution from sludge application may be greater on surface-mined sites than on undisturbed sites, unless efforts are initiated to maintain a heavy vegetative cover.

Site Management

Sites used for application of wastes must be managed in such a way that damage to the land and the environment is minimized. As mentioned elsewhere in this document, the first consideration should be to ensure that wastes do not contain toxic materials which would preclude future use of the land for crop production or some other useful purpose.

Prevention of Erosion

Steps should be taken to prevent soil erosion as a direct result of land application practices. If land is left out of production to allow sludge application during the normal crop growing season, it should be protected with crop residue or a cover crop. In the case of sloping land, it would be wise to alternate strips of cropped land with the strips left out of production.

Sludge injection practices can affect the amount of soil erosion which occurs. Driving the applicator truck across the slope instead of up and down reduces erosion. Injecting sludge parallel to the slope provides channels for water and intensifies erosion potential in the same way as plowing or cultivating up and down the slope.

Prevention of Soil Structure Damage

Applicator trucks with high flotation tires minimize compaction damage in the upper zone of wet soils. However, since compaction in the 30- to 60-cm zone is a function of total axle weight rather than "foot print" pressure, care must be exercised in using applicator trucks on wet soils. Also, using injectors in muddy soils results in much the same type of soil structural damage as plowing when the soil is too wet. Clay soils, in particular, become cloddy and adequate seedbed preparation is very difficult if stirred when wet. The problems are particularly bad when a second injection or a primary tillage pass is made across a field before previously injected sludge is dry.

Prevention of Runoff

In addition to preventing soil loss or damage, the environment must not be degraded by allowing sludge to leave the site by overland flow. Sludge should not be applied on frozen ground or applied on snow so that it is carried off in the melt water. Even sites with a very slight slope will show severe runoff problems from rain or melting snow on top of frozen ground.

Water pollution problems caused by movement of sludge in runoff water can be minimized by use of grassed buffer strips along waterways adjacent to application sites. Grass has been shown to be an effective filter for various wastewater solids and water-borne soil particles.

Odors

Odors can be a nuisance problem in the operation of a sludge disposal system using land application. When an organic material (sludge) undergoes rapid decomposition in limited oxygen conditions, gases such as methane, carbon dioxide, ammonia, hydrogen sulfide, volative organic acids, mercaptans, amines, esters and alcohols will be produced. Some of these gases have unpleasant odors which may cause complaints from residents in the vicinity of the land application site.

The odor potential may be reduced by sludge stabilization, method of land application, method of sludge storage, climatological conditions, site selection, and management.

Sludge is stabilized to make it less odorous and putrescible. Stabilization can be carried out by aerobic or anaerobic digestion, heat treatment, lime addition or composting. Aerobic and anaerobic digestion are the most popular for sludge being applied to land. Aerobic stabilization is the best choice where sludge will not be incorporated with the soil.

The method of application will also affect the potential for odors emanating from the site. Where control of odor problems is necessary, immediate soil incorporation or direct soil injection is recommended (Miller et al., 1979). Thus suitable land such as tilled ground for row crops must be available. Types of equipment suitable for different management schemes are covered under the application section of this chapter.

Sludge may be stored at the treatment plant or at the site of application. If odors from a sludge lagoon are a potential problem, storage at the treatment plant will be the preferred method—assuming the treatment plant is somewhat isolated. Minimizing the lagoon surface by building deep lagoons will help reduce the odor from the lagoon.

Climatological conditions such as temperature and wind will have an effect on the severity of odor when sludge is surface applied. Daily management decisions will be necessary. Spreading in the mornings when the air is warming and rising will help dilute the odor.

The selection of the application site is important to the success of the system. Ideally, the site should be away from a residential area. Experience has shown that odors will sometimes be present. If adjacent property owners are subjected to odors on a regular basis complaints will be sure to follow (Jacobs, 1977; Thorne et al, 1970). In situations where sludge will be applied to farmland not under control of the sewage treatment plant, the individual farmer and sludge applicator must decide on the best system to reduce odor potential. A well managed system with the proper equipment and stabilized sludge will substantially reduce the problem of odor.

Monitoring and Records

One of the most critical aspects of managing land application of municipal and industrial sludges is the monitoring and records program maintained for the given site. Monitoring intensity will depend on the frequency and rate of sludge application, the constituents of concern in the sludge, and whether or not the site is dedicated to long-term sludge application. Accurate and detailed records of all analyses, application dates, and application rates must be maintained during the active period of the site and for several years following the last application. At least four areas should be considered (Knezek and Miller, 1978):

1. Sludge analysis
2. Soil characteristics
3. Groundwater and surface water quality (see exception below)
4. Quality of vegetation produced

Before sludge can be applied, the generating facility or the contract applicator must have the sludge analyzed. Many sludge generating facilities now are aware of this need (Forster et al., 1981). Since the application rates of some elements such as Cd are restricted by law (U.S. Environ. Protection Agency, 1979), analyses are essential. Typical sludge analyses may include nutrients, pH, organic materials, oils, greases, solids content, and metals (Torrey, 1979) depending on the source of sludge and governing guidelines. Once an analysis is obtained, the application rate can be computed. A contract hauler should provide the farmer or landowner detailed information on composition of the sludge applied. This information should be compiled into a separate record for each field to include: sludge analysis, application rates (dry and wet weight), source of sludge, dates of application, planting and harvest dates, application rates of nutrients and metals, sludge pH, history of field use, yield, etc. Some states have computer programs whereby pertinent data are analyzed to provide the farmer with such a record (White and Brown, 1981). Since sludge characteristics are not stable, frequent sludge analysis should be a part of the monitoring program.

The sampling scheme at dedicated sites is crucial. Frequency and location of sampling for groundwater, surface water and soil must be established. Several good discussions on this subject are available (Borchardt et al., 1981; Overcash and Pal, 1979; Torrey, 1979; Knezek and Miller, 1978). The reader is encouraged to consider these references and seek professional assistance in establishing such programs. Groundwater and surface water monitoring on non-dedicated sites may not be required because application rates would typically be much less and at levels not exceeding crop use. On dedicated sites, test wells on the site perimeter and other pertinent locations such as streams, springs, lakes, etc. should be monitored. Seasonal soil sampling is another required practice in most states.

Crop production data must be collected. This will include both yield and analysis of marketable plant tissue. These records are the single best indicator of the effectiveness of land application. Once a program of monitoring and record keeping has begun, it should be continued for some time after sludge is last applied. For dedicated sites, such data collection should be continued indefinitely—even if sludge application rates meet the soil's assimilative capacity for certain parameters.

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Chapter 6

Current Guidelines and Regulations for Agricultural Use of Sewage Sludge in the Southern Region — An Overview

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Increased interest in land application of sewage sludge for agricultural use as well as a low-cost disposal option has spurred most southern states into developing criteria and management plans for environmentally sound implementation of land application. For the most part, states have drawn from federal guidelines and recommendations, and most regulations and laws are in the preliminary rather than final form. At present, only Florida, Kentucky, Louisiana, Oklahoma, Texas, and Virginia have well-defined rules as part of their solid waste management policy. Alabama, Arkansas, Georgia, Tennessee, Mississippi, and North Carolina have published guidelines only.

State Regulations

Although current regulations reflect varying degrees of conservatism or specific conditions within a particular state, restrictions on heavy-metal loading, N management, and toxic organics are quite similar. This chapter will attempt to compile existing state guidelines or regulations to place current knowledge and thinking in perspective. Also, this compilation should assist the states in modifying their individual documents based on experience in other locations.

Sludge may be utilized advantageously for purposes other than crop production (forestry, land reclamation, etc.), but this chapter will address farm use primarily. The tabulated data merely highlight criteria and further details should be obtained by securing appropriate documents or contacting the following state regulatory agencies:

Alabama
Department of Environmental Management

Arkansas
Department of Pollution Control and Ecology

Florida
Department of Environmental Regulations

Georgia
Environmental Protection Division—Department of Natural Resources

Kentucky
Department of Environmental Protection—Division of Waste Management

Louisiana
Solid Waste Management Division—Department of Natural Resources

Mississippi
Department of Natural Resources—Bureau of Pollution Control

North Carolina
Division of Environmental Management—Department of Natural Resources and Community Development

Oklahoma
Solid Waste Division—Industrial and Solid Waste Service—Department of Health

South Carolina
Department of Health and Environmental Control

Tennessee
Division of Solid Waste Management—Department of Health and Environment

Texas
Bureau of Solid Waste Management—Department of Health

Virginia
Bureau of Wastewater Engineering—State Health Department

Site Selection

A number of parameters must be considered in selecting and approving a site for sludge application. Among these are land slope, soil depth to ground water or bedrock, and susceptibility to flooding (Table 6.1). Other factors such as boundaries, distances to surface waters, private wells, dwellings, etc. have been addressed by all states and appear to provide adequate protection. In addition, all states require limited public access to sludge-treated land for a period of one year.

Variability in topographical requirements exists among states with some allowing greater slope if sludge is incorporated upon application (Georgia, Kentucky, Tennessee). Required soil depth to ground water ranges from > 0.6 m (Florida and Oklahoma) to > 3 m (Alabama). The greater minimum depth to ground water specified in the Alabama guidelines reflects strong emphasis on water quality and geologic and hydrologic evaluation by that state. Acceptability of sites located within flood plains is somewhat variable. Whereas, Tennessee and Kentucky restrict application sites to areas above the 10-year flood plain, Alabama, Oklahoma, and Texas limits are based upon the 100-year flood probability. (Oklahoma allows flood plain sites if managed to minimize waste movement).

TABLE 6.1

Site criteria for land application.

State	Slope, %	Depth to ground water in meters	Flood plain constraint
AL	<10	>3	100 Yr
AR	<8	>0.6	—
GA	<5[a]	>1.2	—
KY	<5[a]	>1.2	10
LA	—	>1.0	—
MS	<15	—	—
NC, OK, SC	<5	>0.6	100[b]
TN	<8[a]	>1.2	10
TX	<9	>0.9	100
VA	<12	>1.2	—

[a]Applies to surface treatment. Slopes up to 12% may be utilized if sludge is injected or incorporated.

[b]Sludge must be applied prior to rainy season and followed by vegetative cover.

Monitoring

Considerable variability exists among states with regard to recommendations and/or requirements for monitoring procedures (Table 6.2). Sludge characterization is required by all states, but requirements for parameters other than N and heavy metals and frequency of analyses vary. In most instances soil pH monitoring is required. Soil tests for metals, crop nutrients, etc. are often requisites as well. Other than Mississippi, which recommends biennial metal analysis of crops, states have very loose policies with regard to crop

TABLE 6.2

Sludge, soil, crop, and water monitoring criteria.

State	Sludge	Soil	Crop	Water
AL	Heavy metals, Cd: Zn ratio, N content	pH, SAR, Zn equivalent	—	Ground water monitoring wells and lysimeters
AR	Nutrients and metals annually	—	Grab samples	—
FL[a]	Nutrients, metals, pH, solids quarterly	pH semi-annually	—	—
GA	Cd, Pb, pH, volatile, solids annually	pH	—	Ground water and surface water if industrial input is great
KY	Nutrients, metals, and solids 1-12 times/yr	pH, NO_3-N, metals annually	Crops for food on infrequent basis	Ground water wells for metals and NO_3-N annually
LA	N, salts, and heavy metals	CEC, pH, N, SAR, metals, organic matter semiannually	—	Monitoring wells if deemed necessary
MS	Metals prior to application and biennially thereafter	—	Metals biennially	—
NC	Production rate and composition, E.P. Toxicity Test	Annual soil test	Not required	Ground water only if N utilization rate is exceeded
OK	E.P. Toxicity Test, N, metals, and solids monthly	pH	Periodic for metals	Ground water wells recommended
SC	—	—	—	—
TN	Nutrients and metals semiannually	pH annually, P, K, and metals every 3 yrs	—	Only if N utilization rates are exceeded
TX	Nutrients and metals semiannually	pH, soil tests	—	—
VA	Nutrients, metals, and toxics from monthly to annually	Metals at various depths annually	Only for poor quality sludge	Ground water for NO_3-N with repeated application

[a] Less frequent analysis for treatment plants with daily flow rates under 5MGD.

TABLE 6.3

Maximum allowable heavy metal concentrations in sludge and maximum allowable heavy metal loading rates.

State	Maximum concentration in sludge					Maximum cumulative loading				
	Zn	Cd	Cu	Ni	Pb	Zn	Cd	Cu	Ni	Pb
	mg/kg - dry weight					kg/ha[a]				
AL[b]	—	25	—	—	—	500	10	250	100	1,000
AR	—	—	—	—	—	500	10	250	100	1,000
FL	10,000	130	3,000	500	1,500	250	5	125	125	500
GA	—	—	—	—	—	560	11.2	280	112	1,120
KY[c]	—	—	—	—	—	560	10	280	112	1,120
LA	—	—	—	—	—	560	11.2	280	112	1,120
MS	—	—	—	—	—	560	11.2	280	112	1,120
NC	—	—	—	—	—	500	10	250	250	1,000
OK	5,000	31	2,500	2,500	9,980	560	10	280	280	1,120
SC	—	25	—	—	—	—	10	—	—	—
TN	—	—	—	—	—	446	8.9	223	89	1,000
TX	2,000	25	1,000	200	1,000	—	10	—	—	784
VA[d]	2,500	25	1,000	200	1,000	445	5	250	100	1,000

[a] At soil pH 6.5 or above and at CEC between 5-15 mg/100 g of soil.
[b] Zn equivalent (Zn + 2 Cu + 8 Ni) in top 15-30 cm of soil must be <250 ppm and Cd:Zn <0.015.
[c] Limit of 5 ppm B, Mo, or Se in sludge for corn, legumes, grasses, forages; also cumulative P should not exceed 1,680 kg/ha.
[d] Other maximum concentrations (mg/kg): B-100, Cr-1,000, Hg-15, Mo-10.

monitoring. Generally, ground water monitoring is site and situation specific with most states waiving this requirement if sludge rates do not exceed the N utilization rate by the growing crop.

Heavy Metal Criteria

Only Florida, Oklahoma, Texas, and Virginia define maximum acceptable concentrations of heavy metals in sludges for use in land farming (Table 6.3). In addition to Zn, Cd, Cu, Ni, and Pb, Virginia also lists limits for B, Cr, Hg, and Mo. Although Florida and Oklahoma allow rather high metal sludges to be used, total loading rates are equal to or less than those permitted by other states or recommended by EPA. Maximum Cd loading ranges from 4.5 to 11.2 kg/ha, with Florida and Virginia favoring the lower rate. Similarly, Florida, Virginia, and Texas recommend somewhat lower amounts of Pb than the other states. Aside from the exceptions noted, the federal EPA standards are generally being followed.

Crop Production Constraints

Most states regulate crop production on sludge-treated land according to federal EPA guidelines. The period of time required between sludge application and planting of fresh vegetable crops varies among states, but most prohibit cropping of leafy vegetables because of heavy metal constraints (Table 6.4). Arkansas allows orchard and processed food crops as well as tobacco to be grown on sludge-amended land if the sludge has been treated to further reduce pathogens. Despite the strong federal

TABLE 6.4

Crop production constraints.

State	Use of sewage sludge unacceptable for
AL	(Case by case evaluation)
AR[a]	Produce crops, home gardens, fresh fruits, nonprocessed foods
FL	Root crops, leafy vegetables, tobacco, raw vegetables, pasture (<1 month after sludge)
GA	Livestock grazing (<1 month after sludge), crops for human consumption (<18 months after sludge)
KY	12 month time limit on leafy vegetables and root crops after last application. Tobacco prohibited for 5 years after last application
LA	Tobacco, leafy vegetables, root crops if Cd application exceeds 0.5 kg/ha/yr
MS	Crops for direct human consumption if harvested <12 months after sludge application
NC	Tobacco, grazing (<1 month after sludge), crops for human consumption (<18 months after sludge)
OK	Dairy grazing (<1 month), crops for human consumption (<18 months)
SC	—
TN	Tobacco, leafy vegetables, root crops, raw vegetables (<12 months)
TX	(As per: EPA 1979. Criteria for classification of solid waste disposal facilities and practices. Federal Register 44(179):53438-53464)
VA	Dairy grazing (<2 months), other livestock (<1 month), root crops, crops consumed raw, tobacco, leafy, vegetables, urban development (<18 months)

[a] Orchard, tobacco, processed food crops may receive sludge if it has been treated to *further reduce pathogens*

recommendation that tobacco not be grown on sludge-treated land because of the Cd uptake hazard, some tobacco-growing states have not addressed the issue adequately. Grazing by dairy and other livestock requires periods of 1 to 6 months from time of sludge treatment.

Application Methods and Rate Criteria

Although several states allow either surface-applied or incorporated sludge for cultivated crops, most require or recommend incorporation within a range of time from immediate to 48 hours after application (Table 6.5). In addition to minimizing odor and insect problems, incorporation usually conserves ammoniacal N which would be lost by volatilization if surface applied. Criteria for determining acceptable annual sludge rates are normally based upon N utilization, whereas cumulative rates are limited by Cd or other metal loadings (see Table 6.3). Oklahoma, Texas, and Virginia impose maximum sludge rates as well as N and metal limits.

Conclusions

The information presented is a brief summary of the current regulatory status in the southern region and will likely undergo modification as additional data is generated and evaluated. Criteria relating to heavy metal loading have been adequately researched, but accurate prediction of N release from sludge remains a problem.

Several states have based their guidelines on rates of N release measured in the Midwest, but these rates would likely be accelerated in the South. The higher release rates must be used when determining N utilization rates.

Traditionally, many municipalities, especially in the Southeast, have disposed of their sludge by lagoon storage. As land use constraints become more critical and the environmental problems associated with ponding are recognized, the trend toward land application will increase.

TABLE 6.5

Sludge application methods and criteria for determining rate of annual application.

State	Method of application	Criteria for determining annual rate
AL	(Not specified)	1.5 times crop uptake on N
AR	Surface or incorporated	2 and 1 times crop uptake of N for surface and incorporated sludge, respectively
FL	Incorporation within 48 hours on unvegetated soils	<560 kg N/ha or <13 mt of sludge/ha
GA	Surface or incorporated	<1.25 kg Cd/ha and/or N requirement
KY	Surface or incorporated	N utilization or Cd
LA	Surface or incorporated within upper meter	<0.5 kg Cd/ha for tobacco, leafy vegetables, root crops (no criteria for other crops)
MS	Incorporation recommended	N utilization or <2.2 kg Cd/ha
NC	Incorporation recommended	N utilization
OK	Incorporation within 2 hours	N or P utilization up to 18 mt sludge/ha (56 mt sludge/ha liftime loading)
SC	—	—
TN	Incorporation preferred	N or P requirement and/or <1.25 kg Cd/ha
TX	Incorporation within 48 hours	N requirement and metal limitation not to exceed 18 mt sludge/ha
VA	Immediate incorporation	N requirement not to exceed 11 mt sludge/ha (35 mt sludge/ha on one-time basis)

References

Anderson, T.J., G.W. Barrett, C.S. Clark, V.J. Elia and V.A. Majeti. 1982. Metal concentrations in tissues of meadow voles from sewage sludge-treated fields. J. Environ. Qual. 11:272-277.

Baxter, J.C., D.E. Johnson and E.W. Kienholz. 1980. Uptake of trace metals and persistent organics into bovine tissue from sewage sludge. Denver project. pp 285-309 in G. Bitton et al. (eds.) Sludge: health risks of land application. Ann Arbor Science Publishers, Ann Arbor, MI.

Baxter, J.C., D.E. Johnson and E.W. Kienholz. 1983. Heavy metals and persistent organics content in cattle exposed to sewage sludge. J. Environ. Qual. 12:316-319.

Baxter, J.C., B. Barry, D.E. Johnson and E.W. Kienholz. 1982. Heavy metal retention in cattle tissues from ingestion of sewage sludge. J. Environ. Qual. 11:616-620.

Bernstein, Leon. 1964. Salt tolerance of plants, USDA Infor. Bul. No. 283.

Berry, C. R., and D. H. Marx. 1977. Growth of loblolly pine seedlings in strip-mined kaolin spoil as influenced by sewage sludge. J. Environ. Qual. 6:379-381.

Bingham, F.T., A.L. Page, R.J. Mahler and T. J. Ganje. 1975. Growth and cadmium accumulation of plants grown on a soil treated with cadmium enriched sewage sludge. J. Environ. Anal. 4:207-211.

Bingham, F.T., A.L. Page, R.J. Mahler, and T.J. Ganje. 1976. Cadmium availability to rice in sludge-amended soil under "flood" and "nonflood" culture. Soil Sci. Soc. Am. J. 40:715-719.

Borchardt, J.A., W.J. Redman, G.E. Jones, and R.T. Sprague, (eds.) 1981. Sludge and Its Ultimate Disposal, Ann Arbor Science Publishers, Ann Arbor, MI. pp. 109-126.

Boswell, F.C. 1975. Municipal sewage sludge and selected element applications to soil: effect on soil and fescue. J. Environ. Qual. 4:267-273.

Boswell, F. C. 1981. Evaluation of municipal sewage sludge for land treatment in crop production. Univ. of Ga. Exp. Sta. Bull. 267.

Bray, B.J., R.H. Dowdy, R.D. Goodrich, and D.E. Pamp. 1985. Trace metal accumulation in tissues of goats fed silage produced on sewage sludge-amended soil. J. Environ. Qual. 14:114-118.

Brockway, D. G., and D. H. Urie. 1983. Determining sludge fertilization rates for forests from nitrate-N in leachate and groundwater. J. Environ. Qual. 12:487-492.

Brown, K. W., H. Brawand, J. C. Thomas, and G. B. Evans. 1982. Impact of simulated land treatment of oily sludges and ryegrass emergence and yield. Agron. J. 74:257-261.

Burns, R. E., and F. C. Boswell. 1976. Effect of municipal sewage sludge on rooting of grass cuttings. Agron. J. 68:382-384.

Castellanos, J. Z., and P. F. Pratt. 1981. Mineralization of manure nitrogen—correlation with laboratory indexes. Soil Sci. Soc. Am. J. 45:354-357.

Chaney, R. L. 1980. Health risks associated with toxic metals in municipal sludge. In G. Bitton et al. (eds.), Sludge: health risks of land application. pp. 59-83. Ann Arbor Science Publishers Inc. Ann Arbor, MI.

Chaney, R. L. 1982. Fate of toxic substances in sludge applied to cropland. In Proc. International Symposium on land application of sewage sludge, Tokyo, Japan.

Chaney, R. L., and C.A. Lloyd. 1979. Adherence of spray-applied liquid digested sewage sludge to tall fescue. J. Environ. Qual. 8:407-411.

Chescheir, G. M., III. 1984. Rapid methods for determining the nutrient content and nitrogen availability in liquid manure. M.S. Thesis, N. C. State University, Raleigh.

Council for Agricultural Science and Technology. 1980. Effect of sewage sludge on the cadmium and zinc content of crops. Report No. 83.

Cox, F.R., and J.I. Wear (eds.). 1977. Diagnosis and correction of zinc problems in corn and rice production. Southern Coop. Series Bull. 222 for Regional Res. Proj. S-80. N. C. State University, Raleigh, N.C.

Dowdy, R.H., B.J. Bray and R.D. Goodrich. 1983. Trace metal and mineral composition of milk and blood from goats fed silage produced on sludge amended soil. J. Environ. Qual. 12:473-478.

Dunigan, E.P., and R.P. Dick. 1980. Nutrient and coliform losses in runoff from fertilized and sewage sludge-treated soil. J. Environ. Qual. 9:243-250.

Dunlop, W.R. 1981. The effects of sludge addition to soils high in organic matter. M.S. Thesis, Dept. Soil Sci., N.C. State Univ., Raleigh.

Ellis, B.G. and B.D. Knezek. 1972. Adsorption reactions of micronutrients in soils. In J.J. Mortvedt, P.M. Giordano and W.L. Linsay (eds.) Micronutrients in agriculture. Soil Sci. Soc. Amer. Madison, WI.

Ettlich, W.F. 1977. Transport of sewage sludge. EPA-600/2-77-216 U.S. Environ. Protection Agency, Cincinnati, Ohio.

Fitzgerald, P.R. 1980. Observations on the health of some animals exposed to anaerobically digested sludge originating in the Metropolitan Sanitary District of Greater Chicago System. In G. Bitton, et al. (eds.) Sludge: health risks of land application. pp. 267-284 Ann Arbor Science Publishers, Ann Arbor MI.

Forster, D.L., T.J. Logan, R.H. Miller and R.K. White. 1981. Sewage sludge land spreading in Ohio communities. 1980. Perspective. Research Bulletin 1134. Ohio Ag. Research and Development Center, Wooster, Ohio.

Frank, F., H.E. Braun, M. Holdrinet, K.I. Stonefield, J.M. Elliot, B. Zilkey, L. Vickery and H.H. Cheng. 1977. Metal contents and insecticide residues in tobacco soils and cured tobacco leaves collected in southern Ontario. Tobacco Sci. 21:74-80.

Fuller, W.H. 1978. Investigations of landfill leachate pollutant attenuation by soils. US Environ. Protection Agency Report EPA-600/2-78-158.

Giordano, P.M., and D.A. Mays. 1981. Plant nutrients from municipal sewage sludge. Ind. and Eng. Chem. Product Research Development 20:212-216. (American Chemical Society).

Giordano, P.M., and D.A. Mays. 1983. Crop response to municipal sewage sludge. Presented at meeting of FAO European Network on Trace Elements, Aarhus Denmark, May 31-June 3.

Giordano, P.M., J.J. Mortvedt, and D.A. Mays. 1975. Effect of municipal wastes on crop yields and uptake of heavy metals. J. Environ. Qual. 4:394-399.

Giordano, P.M., and J.J. Mortvedt. 1976. Nitrogen effects on mobility and plant uptake of heavy metals in sewage sludge applied to soil columns. J. Environ. Qual. 5:165-168.

Giordano, P.M., D.A. Mays, and A.D. Behel, Jr. 1979. Soil temperature effects on uptake of cadmium and zinc by vegetables grown on sludge-amended soil. J. Environ. Qual. 8:233-236.

Goldstein, N. 1981. The prime movers of sludge. Bio Cycle, March-April. pp. 24-27.

Gray, G.R. and H.C.H. Darley. 1980. Composition and properties of oil well drilling fluids, 4th ed. Gulf. Publ. Div., Houston, Texas.

Hajjar, L.M. 1985. The residual effect of sewage sludge on metal content of tobacco and peanuts. M.S. Thesis, Dept. of Soil Science, North Carolina State Univ. Raleigh.

Healy, W.B. 1968. Ingestion of soil by dairy cows, N.Z.J. Agric. Res. II:487-409.

Hinesly, T.D., D.E. Alexander, K.E. Redborg, and E.L. Ziegler. 1982. Differential accumulations of cadmium and zinc by corn hybrids grown on soil amended with sewage sludge. Agron. J. 74:469-474.

Hinesly, T.D., D.E. Alexander, E.L. Ziegler, and G.L. Barrett. 1978. Zinc and Cd accumulation by corn inbreds grown on sludge amended soil. Agron. J. 70:425-428.

Hodgson, J.F., 1963. Chemistry of the micronutrient elements in soils. In A.G. Norman (ed.). Advances in Agronomy 15:119-159.

Hortenstine, C. C., and D. F. Rothwell. 1968. Garbage compost as a source of plant nutrients for oats and radishes. Compost Science 9(2):23-25.

Jacobs, L.N. (ed.). 1977. Utilizing municipal and sewage wastewaters and sludges on land for agricultural production. North Central Regional Extension Publication No. 52. Michigan State University, East Lansing, MI.

Jenne, E.A. 1968. Controls on Mn, Fe, Co, Ni, Cu and Zn concentrations in soils and water: the significant role of hydrous Mn and Fe oxides. In R.F. Gould (ed.). Trace inorganics in water. Advances in Chemistry Series. Amer. Chem. Soc.

Jones, S.G., K.W. Brown, L.E. Devel, and K.C. Donnelly. 1979. Influence of simulated rainfall on the retention of sludge heavy metals by leaves of forage crops. J. Environ. Qual. 8:69-72.

Juno, A.R.S. and B.G. Ellis. 1968. Chemical and physical properties of iron and aluminum phosphates and their relation to phosphorus availability. Soil Sci. Soc. Am. Proc. 32:216-221.

Keeney, D.R., and R.D. Wildung. 1977. Chemical properties of soils. In L.F. Elliott and F.J. Stevenson (eds.). Soils for management of organic wastes and waste waters. pp. 75-97. Amer. Soc. Agron. Madison, WI.

King, L.D. 1973. Mineralization and gaseous loss of nitrogen in soil-applied liquid sewage sludge. J. Environ. Qual. 2:356-358.

King, L.D. 1979. Waste wood fiber as a soil amendment. J. Environ. Qual. 8:91-95.

King, L.D. 1980. Use of fermentation residue from citric acid production as a soil amendment. J. Environ Qual. 9:443-447.

King, L.D. 1981. Effect of swine manure lagoon sludge and municipal sewage sludge on growth, nitrogen recovery and heavy metal content of fescue grass. J. Environ. Qual. 10:465-472.

King, L.D. 1982. Land application of untreated industrial waste water. J. Environ. Qual. 11:638-644.

King, L.D. 1984. Availability of nitrogen in municipal, industrial, and animal wastes. J. Environ. Qual. 13:609-612.

King, L.D., and W.R. Dunlop. 1982. Application of sewage sludge to soils high in organic matter. J. Environ. Qual. 11:608-616.

King, L.D., A.J. Leyshon, and L. R. Webber. 1977. Application of municipal refuse and liquid sewage sludge to agricultural land. II. Lysimeter study. J. Environ. Qual. 6:67-71.

King, L.D., and H.D. Morris. 1972a. Land disposal of liquid sewage sludge: I. The effect on yield, in vivo digestibility, and chemical composition of coastal bermudagrass (*Cynodon dactylon* L. Pers). J. Environ. Qual. 1:325-329.

King, L.D., and H.D. Morris. 1972b. Land disposal of liquid sewage sludge. II. The effect on soil pH, manganese, zinc, and growth and chemical composition of rye (*Secale cereale* L.). J. Environ. Qual. 1:425- 429.

King, L.D., and H.D. Morris. 1972c. Land disposal of liquid sewage sludge. III. The effect on soil nitrate. J. Environ. Qual. 1:442-446.

King, L.D., and H.D. Morris. 1973. Land disposal of liquid sewage sludge: IV. Effect on soil phosphorus, potassium, calcium, magnesium and sodium. J. Environ. Qual. 2:411-414.

King, L.D., and H.D. Morris. 1974. Nitrogen movement resulting from surface application of liquid sewage sludge. J. Environ. Qual. 3:238-243.

King, L.D. and R.L. Vick, Jr. 1978. Mineralization of nitrogen in fermentation residue from citric acid production. J. Environ. Qual. 7:315-318.

Knezek, B.D. and R.H. Miller, (eds.) 1978. Application of sludges and wastewaters on agricultural land: A planning and educational guide. Environ. Protection Agency Rep. no. MCD-35. U.S. Government Printing Office, Washington, D.C.

Lake, D.L., P.W.W. Kirk, and J.N. Lester. 1984. Fractionation, characterization, and speciation of heavy metals in sewage sludge and sludge-amended soils: a review. J. Environ. Qual. 13:175-183.

Leeper, G.W., 1970. Six trace elements in soils. Melbourne Univ. Press. Carlton, Victoria.

Loehr, R.C., W.J. Jewell, J.D. Novak, W.W. Clarkson and G.S. Friedman. 1979. Land application of wastes: Volume II. Van Nostrand Reinhold Company , New York, NY.

Lutrick, M.C., W.K. Robertson, and J.A. Cornell. 1982. Heavy applications of liquid-digested sludge on three Ultisols: II. Effects on mineral uptake and crop yield. J. Environ. Qual. 11:283-287.

Magdoff, F.R., and J.F. Amadon. 1980. Nitrogen availability from sewage sludge. J. of Environ. Qual. 9:451-455.

Manson, R.J. and C.A. Merrit. 1975. Farming and municipal sludge: They're compatible. Compost Science, July-August 1975, pp. 16-19.

Matthews, M.R., F.A. Miller, and G.J. Hyfantis, Jr. 1981. Florence demonstration of fertilizer from sludge. Ind. and Eng. Chem.; Product Research and Development 20:567-574.

Miller, R.H., T.H. Logan, R.K. White, O.L. Forster and J.N. Stitzlein. 1979. Ohio guide for land application of sewage sludge. Bulletin 598. Cooperative Extension Service, Ohio State University, Columbus. OH.

Mortvedt, J. J., and P.M. Giordano. 1975. Response of corn to zinc and chromium in municipal wastes applied to soil. J. Environ. Qual. 4:170-174.

Olsen, S.R. and F.S., Watanabe. 1957. A method to determine a phosphorus adsorption maximum of soils as measured by the Langmuir isotherm. Soil Sci. Soc. Am. Proc. 21:144-149.

Overcash, M.R. and D. Pal. 1979. Design of land treatment systems for industrial wastes. Ann Arbor Science, Ann Arbor, Mich.

Parker, C.F., and L.E. Sommers. 1983. Mineralization of nitrogen in sewage sludges. J. Environ. Qual. 12:150-156.

Richards, L.A. (ed.) 1954. Diagnosis and improvement of saline and alkali soils. USDA Handbook No. 60.

Robertson, W.K., M.C. Lutrick and T.L. Yuan. 1982. Heavy applications of liquid-digested sludge on three Ultisols: I. Effect on soil chemistry. J. Environ. Qual. II:278-282.

Ryan, J.A., D.R. Keeney, and L.M. Walsh. 1973. Nitrogen transformations and availability of an anaerobically digested sewage sludge in soil. J. Environ. Qual. 2:489-492.

Ryan, J.A., H.R. Pahren, and J.B. Lucas. 1982. Controlling cadmium in the human food chain: a review and rationale based on health effects. Environ. Res. 28:251-302.

Sheaffer, C.C., A.M. Decker, R.L. Chaney and L.W. Douglass. 1979. Soil temperature and sewage sludge effects on metals in crop tissue and soils. J. Environ. Qual. 8:455-459.

Shelton, C.H., and G.M. Lessman. 1978. Quality characteristics of agricultural and waste disposal runoff water. J. Soil and Water Cons. 33(3)134-139.

Shuford, J.W., L.M. Mugwira, W. Tadesse, H. Nall, and F. Folle. 1982. Effects of soil treatment, phosphate rate and pH level on nutrient and metal availability to plants grown in sludge amended soil. Final report to U. S. Environmental Protection Agency. Grant No. R 805456-02.

Simpson, G.G. 1980. Papermill wastes as soil amendments. M. S. Thesis, N. C. State Univ. Raleigh.

Simpson, G.G., B.L. Carlile, L.D. King, and P. S. Blickensderfer. 1983. Paper mill sludges as soil amendments in crop production. J. Tech. Assn. Pulp and Paper Ind. 66(7):71-74.

Sims, T., and F.C. Boswell. 1976. Effect of bentonite on plant availability of sludge-borne heavy metals in soil. J. Environ. Qual. 7:501-505.

Sims, J.T., and F.C. Boswell. 1980. The influence of organic wastes and inorganic nitrogen sources on soil nitrogen, yield and element composition of corn. J. Environ. Qual. 9:512-518.

Smith, S.B., C.P. Houcke, and J.L. Smith. 1982. Ten years of experience with subsurface injection. ASAE Paper No. 82-2501. 1982. ASAE Winter Meeting, Chicago, IL.

Sommers, L.E. 1977. Chemical composition of sewage sludges and analysis of their potential use as fertilizers. J. Environ. Qual. 6:225-232.

Sommers, L.E., 1980. Toxic metals in agricultural crops. In G. Bitton, B.L. Damron, G.T. Edds, and J.M. Davidson (eds.) Sludge: health risks of land application. pp. 105-140. Ann Arbor Science Publishers, Ann Arbor, MI.

Sommers, L.E., D.W. Nelson, and K.J. Yost. 1976. Variable nature of chemical composition of sewage sludges. J. Environ. Qual. 5:303-306.

Sommers, L.E., C.F. Parker, and G.J. Meyers. 1981. Volatilization, plant uptake and mineralization of nitrogen in soils treated with sewage sludge. Water Resources Research Center, Purdue Univ., West Lafayette, Indiana 47907.

Sposito, G., L.J. Lund, and A.C. Change. 1982. Trace metal chemistry in arid-zone field soils amended with sewage sludge; I. Fractionation of Ni, Cu, Zn, Cd, and Pb in solid phases. Soil Sci. Soc. Am. J. 46:260-264.

Steinhilber, P., and F.C. Boswell. 1983. Fractionation and characterization of two aerobic sewage sludges. J. Environ. Qual. 12:529-534.

Stover, R.C., L.E. Sommers and D.J. Silviera. 1976. Evaluation of metals in wastewater sludge. J. Water Pollut. Control Fed. 48:2165-2175.

Taylor, J.M. L.J. Sikora, C.F. Tester, and J.F. Parr. 1978. Decomposition of sewage sludge compost in soil: II. Phosphorus and sulfur transformations. J. Environ. Qual. 7:119-123.

Tester, C.F., L.J. Sikora, J.M. Taylor, and J.P. Parr. 1979. Decomposition of sewage sludge compost in soil. III. Carbon, nitrogen and phosphorus transformations in different sized fractions. J. Environ. Qual. 8:79-82.

Thangudu, P.R., R.W. Taylor, and D.R. Duseja. 1981. Available phosphorus status of an acid soil treated with sewage sludge and farm manure. J. Environ. Sci. Health A16(6) 611-621.

Thorne, M.D., T.D. Hinesly and R.L. Jones. 1970. Utilization of sewage sludge on agricultural land. Agronomy Facts Sm-29. Illinois Cooperative Extension Service. University of Illinois, Urbana, IL.

Torrey, S. (ed.). 1979. Sludge disposal by landspreading techniques. Noyes Data Corporation, Park Ridge, N.J.

Touchton, J.T., L.D. King, H. Bell, and H.D. Morris. 1976. Residual effect of liquid sludge on Coastal bermudagrass and soil chemical properties. J. Environ. Qual. 5:161-164.

U.S. Dept. of Agr., Food and Drug Adm., U. S. Environ. Protection Agency. 1984. Lead, cadmium and other trace elements in U. S. soils and crops. Draft.

U.S. Dept. of Agr. 1973. Agricultural prices. Annual summary 1972. Crop Reporting Board, Statistical Reporting Service, Washington, D.C.

U.S. Dept. Agr. 1978. Agricultural prices. Annual summary 1977. Crop Reporting Board, Statistical Reporting Service, Washington, D.C.

U.S. Dept. Agr. 1983. Agricultural prices. Annual summary 1982. Crop Reporting Board, Statistical Reporting Service, Washington, D.C.

U.S. Environ. Protection Agency. 1974. Process design manual for sludge treatment and disposal. EPA 625/1-74-006. Office of Technology Transfer, Washington, D.C.

U.S. Environ. Protection Agency. 1976. Application of sewage sludge to cropland; appraisal of potential hazards of the heavy metals to plants and animals. EPA 430/9-76-013.

U.S. Environ. Protection Agency. 1979. Criteria for classification of solid waste disposal facilities and practices. Fed. Reg. 44(179):53438-53468.

U.S. Environ. Protection Agency. 1979. Process design manual for sludge treatment and disposal. EPA 625/1-79-011 Municipal Environmental Research Laboratory, Cincinnati, Ohio.

U.S. Environ. Protection Agency. 1983. Process design manual for land application of municipal sludge. EPA-625/1-83-016.

Westerman, P.W., L.D. King, J.C. Burns, and M.R. Overcash. 1983. Swine manure and lagoon effluent applied to fescue. EPA-600/2-83-078.

White, M.C. and R.L. Chaney. 1980. Zinc, cadmium and manganese uptake by soybean from two zinc-and cadmium-amended Coastal Plain soils. Soil Sci. Soc. Am. J. 44:308-313.

White, R.K. and R.E. Brown. 1981. Applying municipal sludge at agronomic rates. Bio Cycle, January-February pp. 20-44.

White, R.K., T.J. Logan, A.R. Pugh and D.D. Southgate. 1982. Ohio guide for land application of sewage sludge. Extension Bulletin 598. Ohio State University, Columbus.

White, R.K., J. Perry and R.E. Brown. 1980a. Applying municipal liquid sludge to cropland in Ohio. ASAE Paper No. 80-2098. ASAE Summer Meeting, San Antonio, TX.

White, R.K., J. Perry and R.E. Brown. 1980b. Applying municipal sludge cake to cropland in Ohio. ASAE Paper 80-2096. ASAE Summer Meeting, San Antonio, TX.

Williams, P.H., J.S. Shenk, and D.E. Baker. 1978. Cadmium accumulation by meadow voles (*Microtus pennsylvanicus*) from crops grown on sludge-treated soil. J. Environ. Qual. 7:450-454.

Wolnik, K.A., F.L. Fricke, S.G. Capar, G.L. Braude, M.W. Meyer, R.D. Satzger and R.W. Kuennen. 1983. Elements in major raw agricultural crops in the United States. 2. Other elements in lettuce, peanuts, potatoes, soybeans, sweet corn and wheat. J. Agric. Food Chem. 31:1244-1249.

APPENDIX TABLE 1.
Characteristics of municipal sludges.[a]

Location	No. of samples	Solids	N Liquid	N Solids	P	K	Ca	Mg	Na	Pb	Zn	Cu	Ni	Cd	Cr
		%	mg/L	% dry weight						mg/kg					
ALABAMA															
Not specified	1	—	—	1.5	5.3	0.11	6.0	0.50	—	300	14,000	—	—	60	13,600
Decatur	1	—	—	2.3	1.6	0.10	2.5	0.10	—	530	1,800	730	20	50	350
Florence	—	2.6	180	1.1	1.9	0.25	1.3	0.16	0.14	317	770	376	180	15	970
Huntsville	—	—	—	1.6	4.3	0.01	1.5	0.20	—	335	2,500	2,700	405	80	—
Huntsville	—	—	—	2.1	1.8	0.02	2.0	0.11	—	295	3,750	3,375	323	75	—
Tuscumbia	1	—	—	1.6	3.2	0.10	2.4	0.20	—	1,570	1,810	910	290	50	520
FLORIDA															
Pensacola	—	3	—	3.7	1.4	0.12	1.5	0.12	0.16	485	2,440	588	35	12	220
GEORGIA															
Albany	—	—	—	5.0	2.4	0.44	2.6	0.46	—	384	1,410	323	140	9	1030
Americus	—	—	—	—	3.2	0.26	2.2	0.08	—	—	2,420	147	—	—	—
Athens															
Bailey Street	4	4.8	520	3.6	0.9	0.18	1.6	0.12	0.03	—	2.820	520	26	—	—
Macon Highway	7	7.1	340	2.6	0.7	0.16	1.3	0.007	0.02	—	2,180	415	25	—	—
Atlanta	8	—	—	2.2	0.8	0.12	1.1	0.12	—	2,750	11,810	636	—	165	1,754
Atlanta	—	—	—	2.0	1.7	0.15	1.7	0.22	—	2,560	7,590	512	189	114	1,040
Cartersville	—	—	—	4.7	1.1	0.23	0.9	0.26	—	230	1,860	236	18	11	143
Griffin	—	23	—	2.5	1.3	0.07	1.6	0.11	—	447	1,910	352	—	18	358
Griffin	1	68	—	1.4	0.9	0.20	1.0	0.07	—	170	710	149	17	6	130
Griffin	—	—	—	2.9	1.3	0.08	2.3	0.17	—	1,030	1,954	401	90	18	742
Norcross	—	—	—	2.6	0.9	0.05	2.5	0.13	—	740	—	180	27	8	55
Norcross	—	—	—	2.6	—	—	—	—	—	454	1,130	318	30	6	255
Thomaston	—	—	—	4.7	1.6	0.28	0.8	0.21	—	220	1,450	451	44	11	288
Winder	—	—	—	2.0	1.6	0.23	0.06	0.10	—	389	1,010	316	36	9	53
Winder	—	—	—	2.0	—	—	—	—	—	612	21,000	158	11	4	112
LOUISIANA															
Baton Rouge	4	12	—	3.0	0.4	0.22	—	—	—	—	—	—	—	—	—
MARYLAND															
Beltsville															
Blue Plains	1	—	—	0.7	3.1	0.12	1.7	0.26	0.05	510	1,470	700	38	21	800
NORTH CAROLINA															
Albermarle	1	4.8	47	4.0	0.9	0.31	1.1	0.31	—	120	1,750	3,070	35	<1	820
Asheville	5	2.2	730	2.9	1.6	0.51	1.3	0.52	—	214	2,700	685	138	90	380
Charlotte	1	—	—	3.0	2.0	0.78	2.7	0.26	—	530	2,000	390	85	38	465
Clayton	1	2.3	400	4.8	1.1	0.14	1.4	0.16	—	370	1,650	2,070	31	<1	211
Clayton	1	—	—	3.5	1.1	0.13	1.3	0.13	—	280	1,750	2,010	32	4	240
Elizabeth City	1	—	720	2.4	1.5	0.10	1.0	0.18	—	385	1,540	333	43	97	500
High Point	2	4.4	620	3.6	1.6	0.16	1.6	0.32	0.25	1,110	3,980	1,800	954	23	3,300
King's Mountain	1	—	—	2.8	0.9	0.97	0.4	0.22	—	880	1,640	6,320	41	10	540
Kinston	1	0.6	22	6.6	2.1	0.28	0.8	0.13	—	70	940	200	80	9	5,130
Lenoir															
Gunpowder Creek	1	4.5	18	3.1	2.2	0.19	1.2	0.24	—	220	980	1,280	25	6	65
Gunpowder Creek	1	—	—	2.5	2.1	0.14	1.1	0.20	—	180	920	1,400	25	6	60
Lower Creek	1	6.0	25	3.6	1.2	0.27	1.0	0.26	—	150	1,270	260	15	6	790
Lower Creek	1	—	—	2.5	1.2	0.17	1.0	0.24	—	150	860	230	16	7	640
Morganton	2	2.8	420	7.5	1.3	0.18	0.2	0.21	—	105	5,100	980	20	5	80
Pilot Creek	1	—	—	3.9	0.9	0.11	0.2	0.19	—	100	620	510	28	3	1,130
Raleigh	9	4.4	290	6.3	2.2	0.37	1.1	0.27	—	270	700	436	80	13	630
Washington	1	—	—	1.7	4.2	0.10	0.3	0.07	—	155	1,700	266	30	10	63
Wilmington	1	—	—	0.6	1.6	0.07	2.2	0.19	0.06	500	1,920	475	32	13	147
TEXAS															
Corpus Christi	1	—	—	—	—	—	—	—	—	156	1,400	724	—	10	—

[a]— = Data not reported.

APPENDIX TABLE 2.
Characteristics of industrial wastes from several southern states (L.D. King, unpublished data unless otherwise noted).

		N in													
Type	**Solids**	**Liquid**	**Solid**	**P**	**K**	**Ca**	**Mg**	**Pb**	**Zn**	**Cu**	**Ni**	**Cd**	**Cr**	**Sb**	**Ash**
	%	*mg/L*	-------	------- *% dry wt.*	-------	-------	-------	-------	-------	-------	------- *mg/kg*	-------	-------	-------	*% dry wt.*
TEXTILE															
Liquid sludge from lagoons	na[a]	42	1.0	0.28	0.09	0.23	0.10	160	900	482	155	2	1220	170	76
	na	18	2.8	0.88	0.16	0.17	0.21	210	1800	416	40	3	3170	635	48
	6.9	na	2.3	1.10	0.22	0.81	0.24	250	594	490	34	5	3150	na	49
	8.5	na	1.6	0.78	0.25	0.54	0.24	135	542	320	38	4	1830	na	43
	na	16	5.4	0.61	0.24	0.12	0.35	70	1000	760	109	3	570	30	25
	13.5	na	6.8	1.96	0.23	0.72	0.23	140	1400	216	46	4	5560	<1	39
	0.6	22	6.8	2.05	0.28	0.75	0.13	70	940	200	80	9	5130	181	30
Liquid sludge from digester	0.7	112	2.8	1.08	0.27	0.74	0.23	120	557	480	36	5	1730	na	48
Dewatered	na	na	7.9	0.85	0.34	0.52	0.26	9	50	159	31	<1	41	20	14
FERMENTATION															
Filtercake:															
(a) Enzyme prod.	21.7	na	2.2	0.22	0.03	0.14	0.02	<1	40	13	8	<1	10	<1	37
(b) Citric acid prod.	54	na	2.0	0.13	0.06	5.20	0.03	6	8	3	na	<1	4	na	66
Spent brewers yeast	12.8	680	6.2	0.16	0.24	0.04	0.03	1	5	3	<1	<1	<1	1	na
	14.8	340	7.0	na	na	na	na	na	na	na	na	na	na	na	na
Brewery trt. plant sludges	na	na	2.1	0.76	0.09	9.81	0.18	95	975	210	34	3	540	na	na
	na	19	4.7	0.57	0.11	7.45	0.14	40	245	177	29	3	32	<1	49
POULTRY PROCESSING															
Sludge:															
(a) Waste activated	0.8	157	8.0	2.04	0.25	0.06	0.18	80	540	100	30	<1	835	100	18
(b) DAF[b]	8.6	450	3.7	0.78	0.03	0.27	0.03	<1	183	24	2	<1	35	30	4
WOOD PROCESSING															
Waste fiber + binder[c]	na	na	2.3	0.10	0.01	0.27	0.03	<1	28	<1	6	<1	<1	<1	6
Trt. plant sludges	na	na	1.3	0.09	0.07	5.10	0.10	<1	81	30	13	<1	9	<1	21
	12.4	na	0.6	0.13	0.16	0.78	0.19	90	337	78	60	2	362	<1	45
	na	na	0.2	na	na	na	na	38	194	91	84	4	53	120	na
Fly ash:															
(a) Coal	na	na	0.3	0.01	0.11	0.48	0.06	35	65	75	492	<1	35	<1	62
(b) Wood	na	na	0.1	0.27	9.30	9.76	0.66	90	25	42	60	<1	26	100	67
OILY SLUDGES[d]															
Refinery	—[e]	—	0.1	—	—	—	—	14	555	230	14	3	51	—	41
Petrochem.	—	—	0.1	—	—	—	—	21	656	36	925	4	134	—	25

[a]No analysis.
[b]Dissolved air floation sludge.
[c]Urea formaldehyde binder.
[d]From Brown et al., 1982. Na concentrations were 1730 and 1250 mg/kg, respectively.
[e]No data reported.

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